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STUDY OF ^{18}F BY USE OF (^3He,p) AND (α,d) REACTIONS*

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Abstract

Spectra and angular distributions were obtained for the reactions and conditions listed: $^{16}O(^3He,p)^{18}F$ at $E(^3He) = 19.8$ MeV, from $\theta_{lab} = 9°$ to 170° for ^{18}F excited states below 11.3 MeV excitation; $^{16}O(\alpha,d)^{18}F$ at $E(\alpha) = 40.3$ MeV, from $\theta_{lab} = 8°$ to 80° for ^{18}F excited states below 12.7 MeV excitation. Distorted-wave (DW) calculations for the (^3He,p) reaction were compared to experimental angular distributions and relative total cross sections. Agreement was found when a spin-independent interaction potential was used. Nuclear wave functions used in the calculations are discussed.

Spectroscopic and configuration assignments were made or confirmed on the basis of excitation energy, angular distributions, comparison of (α,d) and (^3He,p) results, relative total cross sections, and comparison of experimental quantities to DW calculations.

Configurations and J^π values of 3^+ and 4^+ were suggested for ^{18}F levels at 3.358 and 5.594 MeV excitation energy respectively. Configurations and $J^\pi T$ values were confirmed for some levels at T = 0 assignments were made for a large number of levels. A new ^{18}F level at an excitation energy of 8.596 ±0.019 MeV was identified.

*Work performed under auspices of the U.S. Atomic Energy Commission.

NUCLEAR REACTIONS $^{16}O(^3He,p)$, E = 19.8 MeV; measured $\sigma(E_p,\theta)$.
$^{16}O(\alpha,d)$, E = 40.3 MeV; measured $\sigma(E_d,\theta)$.
^{18}F deduced level, J,π,ℓ. Natural target.

1. Introduction

The (^{3}He,p) and (α,d) reactions were used to study wave functions and spectroscopy of ^{18}F. Glendenning[1]) has discussed the mechanism and usefulness of two-nucleon transfer reactions, and in an earlier paper[2]) concerning the (^{3}He,p) reaction on ^{12}C, a brief outline of two-nucleon transfer reaction formalism was given as well as a discussion of several points pertinent to the application made in this present paper. A discussion of the experimental method and equipment used in this study was also given in ref. 2.

2. Experimental Results

^{3}He and α particle beams of approximately 19.8 MeV and 40.3 MeV respectively obtained from the Berkeley 88-inch cyclotron, were used to study the ^{16}O(^{3}He,p)^{18}F and ^{16}O(α,d)^{18}F reactions. A gas target containing approximately 99.5% ^{16}O was used in the experiments. Energy spectra for the two reactions are shown in fig. 1. The full width at half maximum of a spectrum peak for a "sharp" level was approximately 140 keV.

Background counts were subtracted from each spectrum as follows. No subtraction was made below an excitation of approximately 6.5 MeV. By inspection, a line was drawn from zero counts at 6.5 MeV with a slope increasing in counts with excitation energy. The line was drawn below the valleys of the spectrum, and all counts below this line were subtracted as background.

Observed spectral peaks were assigned excitation energy values independently for each reaction. The assigned values are listed in table 1. Angular distributions for a number of ^{18}F levels are shown in figs. 3 to 6 and differential cross sections are tabulated in ref. 3. Total cross sections calculated between 10° and 82° center of mass are also listed in table 1. The following estimated errors affect the cross sections of both reactions: beam integration 3%, dead time and other electronic errors 2%, and target thickness 1%. In addition the following are errors for the ($^3He,p$) reaction: statistical and peak separation 10-30% and background subtraction 1-10%. Errors in relative and absolute total cross sections are, therefore, estimated to be 10-30% and 20-40% respectively depending upon the strength of the state and amount of background subtraction.

Additional errors for the (α,d) reaction are: statistical and peak separation 5-15% and background subtraction 1-5%. Relative and absolute total cross section errors are estimated in this case to be 5-10% and 15-20% respectively.

3. Spectroscopy by Examination of Data and Comparison to other work

The $^{16}O(\alpha,d)^{18}F$ reaction has previously been studied by Harvey et al.[4,5]) at alpha particle energies of 47 MeV and 52 MeV. A comparison of these data with the data reported in this work taken at an alpha energy of 40 MeV shows that the general characteristics are the same at all three energies. Compound-nuclear effects are expected to be negligible at these alpha particle energies.

Eccleshall and Yates[6]) have measured excitation functions of the differential cross section for the reaction $^{16}O(^3He,p)^{18}F$ to the ground state and first excited state of ^{18}F at angles of 15° and 60° between ^3He energies of 4 and 8.5 MeV. Resonant structure was observed in all four excitation functions. Hinds and Hinds[7]) extended these excitation functions to 11.4 MeV ^3He particles. No resonance structure was observed above 8.5 MeV. Hinds and Middleton[8]) have measured the angular distribution to the ground state and four excited states of ^{18}F at E(^{3}He) = 5.9 and 9.16 MeV. Angular distributions are similar at both energies.

Hinds and Hinds[7]) also studied the reaction ^{16}O(^{3}He,pγ)^{18}F at 10 MeV ^{3}He. They measured the angular correlation of the 0.937 MeV gamma ray from the first excited state of ^{18}F in coincidence with protons detected at angles of 36° and 71°. They concluded from their study that a direct two-nucleon stripping process is the predominant reaction mechanism for this reaction at 10 MeV.

Aguilar et al.[9]) have studied the ^{16}O(^{3}He,p)^{18}F reaction at E(^{3}He) = 29 MeV. This reaction was also studied by Polsky et al.[10]) at E(^{3}He) = 15 MeV and by Pühlhofer and Block[11,12]) at E(^{3}He) = 18 MeV. Both groups of workers obtained angular distribution for several transitions to ^{18}F levels. In general our values for the cross sections taken at E(^{3}He) = 20 MeV are 40% lower than the 18 MeV values, however, an error of 30% in the cross-section magnitude is reported for the 18 MeV data. With this uncertainty in the cross section, 20 MeV and 18 MeV data cannot be said to disagree. Bryant et al.[13]) have measured the differential cross section at 0° for the ^{16}O(^{3}He,n)^{18}Ne reaction at E(^{3}He) = 25 MeV and found a value of 2.0 ± 0.4 mb/sr. This is lower than might be expected from comparison with the data of Pühlhofer and Bock[11]) and this work.

Consideration of the work summarized above together with the (^{3}He,n) experiment of Manley and Stein[14]) leads to the same conclusion as that of ref. 2 namely, that for the (^{3}He,p) reaction discussed in this paper, forward angle differential cross sections arise predominantly from direct reaction contributions but compound nuclear contributions are significant—particularly at back angles.

The low lying energy levels of nuclei in the mass 18 isobar arise from three basic configurations. First, positive-parity states are expected to arise from two particles in the (s,d) shell coupled to a closed ^{16}O core[15]. A second group of positive parity states have a (2h4p) configuration[16,17].

Arima et al.[18] on the basis of a weak coupling model, have proposed a $(p1/2)^{-2}_{j=1}(s,d)^{4}_{J=0}$ configuration for the 1^+ level of ^{18}F at E_x = 1.7 MeV. Kuo and Brown[19] as well as Engeland and Ellis[17] have shown that the 2h4p states in ^{18}F should lie at approximately 2.5 MeV excitation. Mixing of these two types of positive parity configurations will be important.

The third type of levels to be found in these nuclei are negative parity levels which are proposed[17,20] to arise from a $(p)^{-1}(s,d)^3$, 1h3p configuration.

If ^{16}O is predominantly a closed shell it follows that only the simple $(s,d)^2$ shell model states would be populated in a two-nucleon stripping reaction on a ^{16}O target. States with 1h3p or 2h4p character are expected to be excited through small components in the ^{16}O wave function or through more complicated mechanisms.

A comparison between known levels of ^{18}F and levels excited strongly enough for positive identification in the $^{16}O(\alpha,d)^{18}F$ and $^{16}O(^{3}He,p)^{18}F$ reactions is made in table 1. In accordance with selection rules the (α,d) reaction is expected to excite strongly only T = 0 states of ^{18}F. On this basis a number of states are definitely or tentatively assigned as T = 0 as indicated in table 1. Other T = 0 assignments are confirmed by this work.

Ollerhead et al.[31] have made tentative assignments for ^{18}F levels corresponding to the T = 1 levels of ^{18}O. The levels at 1.042 and 3.060 MeV excitation energy are well established as indicated in the references of table 1. Note the 3.06 MeV level is not excited in the (α,d) reaction. It is, however, excited in the (^{3}He,p) reaction and, although not resolved from the 3.134 MeV level, is dominant over it as indicated by the excitation energy of the spectral peak corresponding to these two levels.

Assignment of the 4.651, 4.741 and 4.964 MeV levels as 4^+, 0^+ and 2^+ T = 1 levels respectively is consistent with the decay scheme work referred to in table 1. It is also consistent with the level spacing in ^{18}O as is shown in fig. 2. The decay scheme work, however, could not rule against the possibility that the 4.400 MeV state could be the 4^+ T = 1 state. As is shown in table 1 the 4.400-MeV level is excited in the (α,d) reaction and therefore must be assigned T = 0. On the other hand the 4.651, 4.741 and the 4.964 MeV levels are not excited by the (α,d) reaction and are excited by the (^{3}He,p) reaction. These observations confirm the T = 1 assignments to the three levels under consideration.

A $J^\pi = 1^-$ level[34]) of ^{18}O at E_x = 4.45 MeV was proposed[31]) to correspond to one of two levels at 5.59 and 5.566 MeV excitation in ^{18}F. As is seen in table 1, the 5.59 MeV level is excited in both the (α,d) and (^{3}He,p) reactions, which restricts this level to T = 0. The angular distribution of this level is characteristic of L = 4 as shown in fig. 5. Arguments will be presented in section 4 for the assignment of this level as $J^\pi T = 4^+0$. The 5.66 MeV level is not resolved from the 5.59 MeV level just discussed and it is not certain that this level is excited in the (α,d) reaction. It may, therefore, be the $J^\pi = 1^-$ T = 1 level.

The $2^{(-)}$ level in ^{18}F at E_x = 6.23 MeV was proposed[31]) to correspond to the 5.09 MeV level of ^{18}O. The 5.09 MeV level is now known[35]) to be a 3^- level which casts doubt on this proposed correspondence unless the 6.23 MeV level of ^{18}F has been assigned the wrong spin.

The 6.556 MeV level was also suggested[31]) as a T = 1 level. The observation of this level in the (α,d) reaction indicates a T = 0 assignment. The ^{18}F energy levels in the region of 6.5 MeV are closely spaced and generally of unknown spins. The assignment of T = 1 levels in this region on the basis of present data, therefore, seems unjustified.

Ollerhead et al.[31]) also suggested that the 6.19 MeV level of ^{18}O (now known[36]) to be $J^{\pi} = 2,3^-$) corresponds to either the 7.315 or the 7.499 MeV level in ^{18}F. Both are tentatively assigned 3^- spin and parity. The 7.499 MeV level must be T = 0 since it is observed in the (α,d) reaction. The 7.315 MeV level may, therefore, be the T = 1 level.

Angular distributions for L = 0, 2, and 4 transitions in the reaction ^{16}O(^{3}He,p)^{18}F are shown in figs. 3 to 5. Angular distributions for the 2.101 and 2.524 MeV levels are shown in fig. 6. As discussed above these two levels and the 1.700 MeV level are considered to be particle-hole states. The angular distributions of the two states first mentioned do not show a direct-stripping pattern while the 1.700-MeV level has an L = 0 strippling-like angular distribution. All three states have a rather small cross section which is to be expected for states of strong particle-hole character. The ^{16}O(t,p)^{18}O data of Middleton and Pullen[37]) contains two states of predominant particle-hole character and both show direct stripping-like angular distributions. The distributions have been reproduced by the calculation of Dönau et al.[38]) which are based upon a simple stripping mechanism. These observations suggest that the 2.101 and 2.524 MeV levels may be excited by reaction mechanisms other than simple stripping.

Pühlhofer and Bock[11]), in their study of the ^{16}O(^{3}He,p)^{18}F reaction at E(^{3}He) = 18 MeV, were able to resolve the four levels of ^{18}F near 1 MeV excitation. Their work shows the 1.042 and 1.081 MeV levels to have cross sections about 1/4 and 1/20 that of the ground state respectively. In the work of this paper, two distinct but only partially resolved peaks near 1 MeV were observed. It is assumed that the lowest energy peak contains a contribution from the 0.937 MeV level only and that the other peak contains contributions from the 1.042, 1.081 and 1.131 MeV levels. A comparison of cross sections for the reaction at 18 and 20 MeV substantiates these assumptions.

In several cases an experimental peak in the spectrum is too broad to resolve individual levels but nevertheless a careful determination of the excitation energy of the peak shows the predominant contribution comes from only one level. If the (^{3}He,p) reaction is considered, several such cases are observed. The 3.062 MeV peak has alread been discussed. A peak at 3.830 MeV must arise predominantly from the proposed 2^+ T = 0 state at this energy. The 3^- T = 0 state nearby thus has a small cross section which is consistent with small cross sections to the other two negative parity levels discussed.

The observed peak at 4.651 MeV must arise predominantly from the known level at that energy. The cross section to the 0^+, T = 1 companion level must therefore be small. The 5.601 MeV peak has been discussed above. A new ^{18}F level at an excitation energy of 8.596 ± 0.019 MeV was observed in the (α,d) reaction.

One further observation is of interest. Of the large number of known energy levels in ^{18}F below an excitation energy of 13 MeV only a relatively few are strongly or moderately excited in these two-nucleon stripping reactions. This observation points up one of the advantages of two-nucleon transfer reactions; that is the preferential population of specific types of states.

4. Distorted Wave Calculations

Distorted wave calculations for the reaction $^{16}O(t,p)^{18}O$ have recently been made by Dönau et al.[38]) which specifically considered the particle-hole configurations for both ^{16}O and ^{18}O. Good agreement between calculated and experimental relative cross sections was found for the seven levels studied. Henley and Yu[39]) have made calculations for the $^{16}O(^{3}He,n)^{18}Ne$ reaction at $E(^{3}He)$ = 20 MeV for the ground state and two excited states of ^{18}Ne. These calculations are not in agreement with experimental values, perhaps because harmonic oscillator radial wave functions were used without correcting their assymptotic behavior.

Pühlhofer and Bock[11,12]) have made calculations for the $^{16}O(^{3}He,p)^{18}F$ reaction at $E(^{3}He)$ = 18 MeV. They calculated angular distributions and total relative cross sections to the ground state and six excited states of ^{18}F below 4 MeV excitation. Polsky et al.[10]) have also made DW calculations for the ground state and six excited state transitions for this system at $E(^{3}He)$ = 15 MeV. No total cross section comparisons were made however. The results of these two sets of calculations are in agreement with those reported here.

Four sets of wave functions for the energy levels of ^{18}F were used for calculations and compared to the experiment. All four sets assume a closed ^{16}O core with two particles in shell-model states. One set was calculated by Kuo and Brown[19]). These workers used the Hamada-Johnston (HJ)[40]) potential to construct an effective two-nucleon interaction. The effective interaction was constructed by allowing the two particles to interact via the HJ potential and by adding an additional interaction of one particle upon the other through polarization of the core. Only single-particle states of the (s,d) shell were included in the calculation.

Inoue et al.[41]) have constructed an effective interaction which includes central, tensor and spin-orbit potentials. Their calculation includes (s,d) shell, single-particle states only (Labeled Arima in figures and tables.)

Redlich[42]) has kindly made available two sets of calculations based upon a simple, central potential. The methods used for the calculation are similar to those reported[43]) for ^{210}Pb calculations. One set of calculations (Redlich), using a triplet-even force 1.5 times the single-even force, included only (s,d) shell, single-particle states. The other set (Redlich(E)) using a triplet-even force 1.25 times the single-even force, included all possible delta-two excitations from the (s,d) shell as well. (A delta-two excitation is the excitation of one particle by $2\hbar\omega$ energy units or the excitation of two particles, each by $1\hbar\omega$ energy unit.)

Each of these calculations employed harmonic-oscillator radial wave functions. The oscillator parameters (ν) used in these nuclear structure calculations were also used in the reaction calculations under discussion: 0.362, 0.339, 0.350, and 0.339 for Arima, Kuo and Brown, Redlich, and Redlich(E) respectively.

The energy levels of ^{18}F and ^{18}O together with the four sets of calculated energy levels are shown in fig. 2. The ground state of ^{18}O has been normalized to the 0^+ T = 1 state of ^{18}F and the ground state of the two Redlich calculations have been normalized to the ^{18}F ground state. The position of the ground states for the other two calculations, relative to the ^{18}F ground state, reflect their calculated binding energy relative to the experimental binding energy of ^{18}F.

Note that for three of the sets no predicted levels fall between 1.5 to 2.5 MeV excitation. Inoue et al.[41]) by means of the tensor force, have lowered a 2^+ and a 1^+ level into this region.

The four sets of calculations discussed above provide two-particle wave functions. The calculation of two-nucleon transfer structure factors for such wave functions are discussed in refs. 1 and 2.

Optical-model parameters used in calculations for the $^{16}O(^{3}He,p)^{18}F$ reaction are shown in table 2. A Woods-Saxon potential was used with V,W, and W_d as the potential depths for the real, volume-imaginary and imaginary-surface derivative potentials respectively. r_v, r_w and r_c are real, imaginary and Coulomb radius parameters. a_v and a_w are the real and imaginary surface-diffuseness parameters.

Sets 5 and 7 were taken from the paper of Hiebert et al.[44]) who used them successfully for $(d,^{3}He)$ calculations. Set 6 is an average of these two. Sets 8 and 10 were obtained by fitting the data of Artemov et al.[45]) Set 9 was obtained by taking the average of sets 8 and 10. Potential set 11 for proton scattering on mass 18 was calculated from the systematic potentials of Perey[46]) and is typical of potentials used in the exit channel. Potential set 12 was obtained by using the potential well depth parameter of set 11 and arbitrarily reducing the geometry parameters to the values shown. DW calculations were made using the program REACTION 6 which employs the zero range and the local potential approximations. Harmonic oscillator functions with matched exponential tail functions were used to describe the bound state, center-of-mass motion of the captured pair. Calculations are based upon a spin-independent interaction potential. (See discussion in ref. 2).

The curves in figs. 3-5 are DW fits normalized to the $^{16}O(^{3}He,p)^{18}F$ data for $E(^{3}He)$ = 20 MeV. The solid curves use optical potential sets 9 and 12 and the dashed curves use sets 6 and 12. The dot-dash curves use potential sets 9 and 11.

Experimental and calculated relative cross sections are listed in table 3. Calculated values are taken from DW fits using the proton optical potential set 11. There is very little difference between the values listed and those based upon potential set 12. The factor F at the bottom of the table is a measure of the goodness of fit and is defined as the average value of the greater ratio between experimental and calculated relative cross sections minus one. F = 0 would be a perfect fit. In general, good agreement with experiment is found. If the level 1^{+}0b is assumed to be the 1.7 MeV level the calculated cross section and angular distribution both appear to be in agreement. However, it should be noted that the cross section is small and this is also to be expected for a particle-hole configuration. The 1^{+}0b level could also be associated with the 3.725 MeV state. A small cross section for this state is also in agreement with the experiment and the excitation energy is in better agreement with the predicted energy of the 1^{+}0b state.

For purposes of comparison, calculations were made for the 2^{+}0a state at both 2.524 and 3.838 MeV excitation. The 2^{+}0a must be assigned to the 3.838 MeV level on the basis of relative cross section and on the basis of angular distribution.

The relative cross section and L = 2 angular distribution of the 3^{+}0b agrees well with experimental observations for the 3.358 MeV state. The 4.108 MeV state is also a possible choice for the 3^{+}0b assignment even though its cross section is nearly twice the predicted value and does not show the L = 2 angular distribution, as the 4.218 MeV level may be making a contribution to the cross section reported. Indeed Polsky et al.[10)] have tentatively assigned the 3^{+}0b to the 4.108 MeV level based upon the $^{17}O(^{3}He,d)^{18}F$ reaction. Their extraction spectroscopic factor is in good agreement with the predictions of Kuo and Brown[19)].

Excellent agreement in the relative cross sections of the 4^+a, 0^+b, and 2^+b T = 1 states and agreement in the angular distribution for the 4^+a and 0^+b states confirms the suggested assignment[31)] of these levels.

The predicted cross section to the 5.594 MeV states is not in as good agreement with experiment as predictions to other levels; nevertheless, a relatively strong level is predicted which agrees qualitatively with the observation. This fact, together with the very characteristic L = 4 angular distribution, makes an argument for a 4^+ T = 0 assignment to this level.

A few comments concerning the wave functions used in these calculations are in order. It appears that the calculations of Inoue et al.[41)] predict the 2^+a T = 0 level at too low an excitation energy. Arima[41)] has suggested that this may mean the tensor force, which lowered this state, is too strong or that a stronger spin-orbit force may be needed to raise the state to higher excitation. In this connection, it is interesting to note that the potential used by Kuo and Brown[19)] also included tensor and spin-orbit forces but gives a better excitation energy for the 2^+a T = 0 level.

The higher configurations included in the wave functions of the Redlich(E)[42)] calculation do not improve the fit in general. This may indicate that such higher configurations do not contribute to low lying levels of ^{18}F, or as Redlich[42)] has suggested, that the simple potential used does not properly mix these configurations.

It appears significant that the Kuo and Brown[19)] calculations, using the HJ free nucleon potential, compare so favorably with other shell model calculations.

A comparison of the DW calculations of Dönau et al.[38]) which account for particle-hole character of wave functions, and those of this work and of Pühlhofer and Bock[11]) which consider only two-particle configurations shows the same degree of agreement between theory and experiment. The reason for this is to be found in the fact that the particle-hole configurations contributed little to the strength of the transition[38]). The advantage of the more complete treatment is that it allows DW calculations to be made for states of predominant particle-hole character and, therefore, tests the amount of two-particle configuration mixed into these states.

One weakness of the wave functions used by Dönau et al.[38]) may be that they consider only p 1/2 holes in the ^{16}O core. It was shown by Mangelson et al.[2]) in studies of the $^{12}C(^{3}He,p)^{14}N$ reaction that when the transferred particles involve the p shell it is important to consider intermediate coupling wave functions and therefore, p3/2 holes.

5. Summary

The following spectroscopic information for ^{18}F was obtained in this work. The 2.524 MeV $2^{+}0$ level[23]) was shown to have little $(s,d)^2$ configuration. This conclusion was based on the nature of its angular distribution and the magnitude of its cross section. On similar evidence the 3.838 MeV $2^{+}0$ level[24]) was associated with the $2^{+}0a$ $(s,d)^2$ state. Although a particle-hole configuration has been suggested for the 1.700 MeV state[17]) these experiments were unable to eliminate an $(s,d)^2$ configuration for this state. The 3.358 MeV level[24] was tentatively associated with the $3^{+}0b$ $(s,d)^2$ state. These conclusions are supported by the recent work of Pühlhofer and Bock[11]) and of Polsky et al.[10]).

By comparison of the reactions (α,d) and (^{3}He,p) on a ^{16}O target the following observations, not made by the above mentioned workers, were made in this work. The 4.400 MeV level[24] was excited in the (α,d) reaction and is, therefore, a T = 0 level. A comparison of the two reactions indicated that the 4.652, 4.742 and 4.964 MeV levels[31] are not T = 0. These levels were confirmed as the 4^+a, 0^+b and 2^+b T = 1 levels respectively by the agreement of their relative cross sections to predicted values. The 5.594 MeV level was associated with the 4^+0a $(s,d)^2$ state. It was excited in both reactions, had an L = 4 angular distribution, and its cross section was in qualitative agreement with calculated values. In addition to these levels, 22 other levels were either assigned or confirmed as T = 0 states. A new ^{18}F level at an excitation energy of 8.596±0.019 MeV was identified.

The above spectroscopic assignments were based in part upon reaction calculations for ^{16}O(^{3}He,p)^{18}F using ^{18}F wave functions of Inoue et al.[41], Redlich[42,43] and Kuo and Brown[19]. Relative cross sections calculated using four sets of wave functions from these workers are all in good agreement with the data. Inoue et al.[41] predict the 2^+0a at about 2.5 MeV excitation. As mentioned above, this shell model level is found experimentally at 3.838 MeV excitation. It must, therefore, be concluded that in the limited, shell-model space of the (s,d) shell, Inoue et al.[41] have chosen the wrong effective interaction. A comparison of the two Redlich[42,43] calculations, one based on $(s,d)^2$ configurations and other including, in addition, higher configurations, indicates that for the simple effective interaction used, the higher configurations make no significant changes in the wave functions. It is most satisfying to note that the calculations of Kuo and Brown[19], which are based on a free nucleon-nucleon interaction potential, are as good as calculations based on an impirical effective interaction.

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Figure Captions

Fig. 1. Proton energy spectrum for the $^{16}O(^3He,p)^{18}F$ reaction at $E(^3He)$ = 19.8 MeV: Deuteron energy spectrum for the $^{16}O(\alpha,d)^{18}F$ reaction at $E(\alpha)$ = 40.3 MeV.

Fig. 2. Energy level diagram of ^{18}F with a comparison to levels of ^{18}O and to calculations of Inoue et al.[41]) (Arima), Redlich[42,43]) and Kuo and Brown[19]). See also references of table 1.

Fig. 3. Proton angular distributions for the $^{16}O(^3He,p)^{18}F$ reaction at $E(^3He)$ = 19.8 MeV. The g.s. transition is of predominant L = 0 character and the 1.704 MeV transition may have L = 0 character. The solid Line curves are DW calculations using ^3He optical model potential sets 9 and 12, the dashed line curve is a DW calculation using sets 6 and 12, and the dot-dash curves are DW calculations based upon sets 9 and 11. Statistical errors are indicated by error bars or are smaller than the point symbols.

Fig. 4. Proton angular distributions for transitions of predominant L = 2 character. The curves labeled 2^+, 0a and 1^+, 0b are in proper relative proportion to each other. See caption of fig. 3.

Fig. 5. Proton angular distributions for transitions of predominant L = 4 character. The pairs of curves for the first two transitions are in proper relative proportion to each other. See caption of fig. 3.

Fig. 6. Proton angular distributions for transitions of predominant particle–hole character. See caption of fig. 3.

Table 1 Fluorine 18: energy levels and cross sections at $E(^{3}He) = 19.8$ MeV and $E(\alpha) = 40.3$ MeV.

Experimental		This Work						Dominant Configuration	References[a]
		$^{16}O(\alpha,d)^{18}F$			$^{16}O(^{3}He,p)^{18}F$				
Energy[a] (MeV)	J^{π} T[b]	Energy (MeV ± keV)		σ[c] (mb)	Energy (MeV ± keV)		σ[d] (mb)		
0.0	1^{+} 0	0.0	17	0.85	0.0	7	2.42	$(s,d)^{2}$	8,21-24
0.9371	3^{+} 0	0.934	14	1.89	0.937	8	6.10	$(s,d)^{2}$	8,21,23-25
1.0417	0^{+} 1							$(s,d)^{2}$	8,21-26
1.0807	0^{-} 0							$(p)^{-1}(s,d)^{3}$	8,20,21,23-25,27-29
1.1310	5^{+} 0	1.119	16	8.46	1.111	7	4.96	$(s,d)^{2}$	8,21,23-25
1.7005	1^{+} 0	1.716	18	0.13	1.680	24	0.45	$(p)^{-2}(s,d)^{4}$	18,19,21,23-25,30
2.1008	2^{-} 0	2.100	11	0.27	2.096	13	1.05	$(p)^{-1}(s,d)^{3}$	20,23-25,27,28
2.5235	2^{+} 0[e]	2.541	19	0.10	2.509	18	0.46	$(p)^{-2}(s,d)^{4}$	19,21,23-25,30
3.0603	2^{+} 1				3.062	15	3.04	$(s,d)^{2}$	21-26,30,31
3.1339	1^{-} 0	3.122	14	0.13				$(p)^{-1}(s,d)^{3}$	20,21,23-25,30
3.3581	$2,(3)^{+}$ 0[e]	3.363	20	0.22	3.352	16	0.70	$(s,d)^{2}$	21,23-25,29,30
3.7248	1 0							$(s,d)^{2}$	24,25,29
3.790	$1,2,(3^{-})$ 0							$(p)^{-1}(s,d)^{3}$	20,24,25,29
3.8385	2^{+} 0[e]	3.808	12	0.89	3.830	12	6.41	$(s,d)^{2}$	24,25,29
4.108	1,2,(3) 0[e]	4.140	12	0.44	4.134	11	1.02		29
4.218	1,(2)								24,29
4.350	2,3								24,29
4.400	≥2 0[e]	4.393	9	0.55	4.378	9	1.90		24,29
4.651	4^{+} 1[e]				4.651	12	2.45	$(s,d)^{2}$	22-24,26,29,31,32
4.741	0^{+} 1[e]							$(s,d)^{2}$	22,24,26,29,31,32

Table 1. (continued)

Experimental		This Work						Dominant Configuration	References[a]
		$^{16}O(\alpha,d)^{18}F$			$^{16}O(^{3}He,p)^{18}F$				
Energy[a] (MeV)	J^{π} T[b]	Energy (MeV ± keV)		σ[c] (mb)	Energy (MeV ± keV)		σ[d] (mb)		
4.844	1 0[e]	4.852	10	0.55	4.843	12	1.36		29
4.964	2^+ 1[e]				4.967	21	0.61	$(s,d)^2$	26,29,31
5.295	0[e]	5.266	34		5.297	25	0.48		29
5.502									
5.594	(4^+)0[e]	5.590	27	0.37	5.601	12	2.71	$(s,d)^2$	
5.662	$(1,2^-)$(1)								31
5.786	0[e]	5.785	31						
6.092					6.105	8	5.62		
6.139	0[e]	6.139	12	1.68					
6.233	$2^{(-)}$(1)								31
6.247	(1^+)				6.265	13	3.38		
6.376									
6.472									
6.556	$(3,4,5^+)$0[e]	6.548	18	0.60					
6.634									
6.636	1^-								
6.765					6.779	7	7.67		
6.800	2^- 0[e]	6.807	10	1.17					
6.859									

Table 1. (continued)

Experimental		This Work						Dominant Configuration	References[a]
		$^{16}O(\alpha,d)^{18}F$			$^{16}O(^{3}He,p)^{18}F$				
Energy[a] (MeV)	J^{π} T^{b}	Energy (MeV ± keV)		σ^{c} (mb)	Energy (MeV ± keV)		σ^{d} (mb)		
7.185	$(4^{+})0^{e}$	7.191	8	1.02	7.206	9	3.08		
7.26	(1^{+})								
7.315	$(3^{-})(1)$								31
7.493	$(3^{-})(0)^{e}$	7.434	13	0.51					
7.54									
7.60	$(0)^{e}$								
7.69	$(0)^{e}$	7.658	12	0.50	7.646	14	4.18		
7.72									
7.88	$(2^{-})\ 0^{e}$	7.871	11	0.52	7.874	22	4.06		
7.92	(1^{+})								
8.07									
8.20									
8.22									
8.36									
	0^{e}	8.596	19	0.37					
8.98	$(0)^{e}$	8.861	190	0.43					
9.17					9.145	32	3.38		
9.35									

Table 1. (continued)

Experimental			This Work						Dominant Configuration	References[a]
			$^{16}O(\alpha,d)^{18}F$			$^{16}O(^{3}He,p)^{18}F$				
Energy[a] (MeV)	J^{π}	T^{b}	Energy (MeV ± keV)		σ^{c} (mb)	Energy (MeV ± keV)		σ^{d} (mb)		
9.42						9.404	31	5.69		
9.49		0[e]	9.494	15	1.62					
9.60										
9.67	$2,3^{+}$									
9.79						9.82	40			
9.96		0[e]	9.96	120	0.45					
10.11						10.06	45			
10.27			10.268	12	0.56					
10.38						10.352	25	3.58		
10.51		(0)[e]	10.541	10	1.11					
(10.57)										
10.76										
(10.85)										
10.93						10.96	60	4.42		
11.02										
11.07		0[e]	11.073	37	0.51					
11.16						11.13	50	4.96		
11.39		0[e]	11.384	18	0.46					
11.78										
12.03		0[e]	12.055	16	0.30					

Table 1. (continued)

Experimental		This Work				Dominant Configuration	References[a]
		$^{16}O(\alpha,d)^{18}F$		$^{16}O(^{3}He,p)^{18}F$			
Energy (MeV)	J^{π} T[b]	Energy (MeV ± keV)	σ[c] (mb)	Energy (MeV ± keV)	σ[d] (mb)		
12.51							
12.66	0[e]	12.67	60				
12.94							

[a]Reference 33 was used in addition to those in the reference column.

[b]A parenthesis ( ) indicates a preference or tentative assignment.

[c]Cross sections are integrated from approximately 12° to 80° center of mass.

[d]Cross sections are integrated from approximately 11° to 82° center of mass.

[e]Assignment of J^{π} and/or T and/or configuration made or confirmed by this work.

Table 2. Optical-model parameters for the $^{16}O(^{3}He,p)^{18}F$ reaction.

Particle	Target	Set	V (MeV)	r_V (fm)	a_V (fm)	W (MeV)	W_D (MeV)	r_W (fm)	a_W (fm)	r_c (fm)
^{3}He(10.5 MeV)	^{16}O	5	170	1.03	0.893	20.0		2.06	0.510	1.40
^{3}He(20 MeV)	(average)	6	180	1.08	0.784	15.6		2.12	0.468	1.40
^{3}He(29 MeV)	^{16}O	7	190	1.14	0.675	11.2		2.17	0.426	1.40
^{3}He(16.6 MeV)	^{16}O	8	220	1.01	0.663	5.3		2.21	0.803	1.40
^{3}He(20 MeV)	(average)	9	220	1.11	0.653	7.1		2.11	0.815	1.40
^{3}He(25.8 MeV)	^{16}O	10	220	1.29	0.633	10.4		1.93	0.837	1.40
p (22 MeV)	^{18}F	11	42.6	1.25	0.65		8.4	1.25	0.47	1.25
p (22 MeV)	^{18}F	12	42.6	1.11	0.58		8.4	1.11	0.42	1.11

Table 3. Comparison of relative cross sections for the reaction $^{16}O(^{3}He,p)^{18}F$ at $E(^{3}He)$ = 20 MeV.

Levels				Relative Level Cross Sections[a]				
Experiment		Theory[b]	Experiment	Arima[d]	Arima[d]	Kuo & Brown[d]	Redlich[d]	Redlich(E)[d]
(MeV)	J^π T	J^π Tx	V^c =	180	220	220	220	220
0.0	1^+ 0	1^+ 0a	1.0	1.1	1.0	1.0	1.0	0.9
0.9371	3^+ 0	3^+ 0a	2.5	2.5	2.5	2.5	2.5	2.9
1.0417	0^+ 1	0^+ 1a						
1.0807	0^- 0		2.0	1.5	2.2	2.0	2.1	2.2
1.1310	5^+ 0	5^+ 0a						
1.7005	1^+ 0	1^+ 0b	0.2	0.2	0.2	0.2	0.3	0.2
2.1008	2^- 0		0.4					
2.5235	2^+ 0	2^+ 0a	0.2	1.8	1.7	1.6	1.6	1.8
3.0603	2^+ 1	2^+ 1a	1.3	1.6	1.5	1.3	1.5	1.6
3.1339	1^- 0							
3.3581	$2(3)^+$ 0	3^+ 0b	0.3	0.1	0.1		0.2	0.2
3.7248	1 0	1^+ 0b						
3.790	1,2,(3^-)0		2.6	2.4	2.2	2.1	2.2	2.4
3.8385	2^+ 0	2^+ 0a						
4.108	1,2,(3) 0		0.4					
4.218	1,(2)							
4.350	2,3		0.8					
4.400	≥2 0							
4.651	4^+ 1	4^+ 1a	1.0	0.8	1.0	0.9	1.0	0.9
4.741	0^+ 1	0^+ 1b						

Table 3. (continued)

Levels					Relative Level Cross Sections[a]				
Experiment		Theory[b]	Experiment		Arima[d]	Arima[d]	Kuo & Brown[d]	Redlich[d]	Redlich(E)[d]
(MeV)	J^{π} T	J^{π} Tx		V^c =	180	220	220	220	220
4.844	1 0		≈ 0.6						
4.964	2^+ 1	2^+ 1b	≈ 0.3		0.4	0.4	0.4	0.3	0.2
5.295	0		0.2						
5.502									
5.594	(4^+)0	4^+ 0a	] 1.1		1.4	1.7		1.7	2.0
5.662	$(1,2^-)$(1)		]						
				F^e =	0.31	0.29	0.18	0.22	0.27

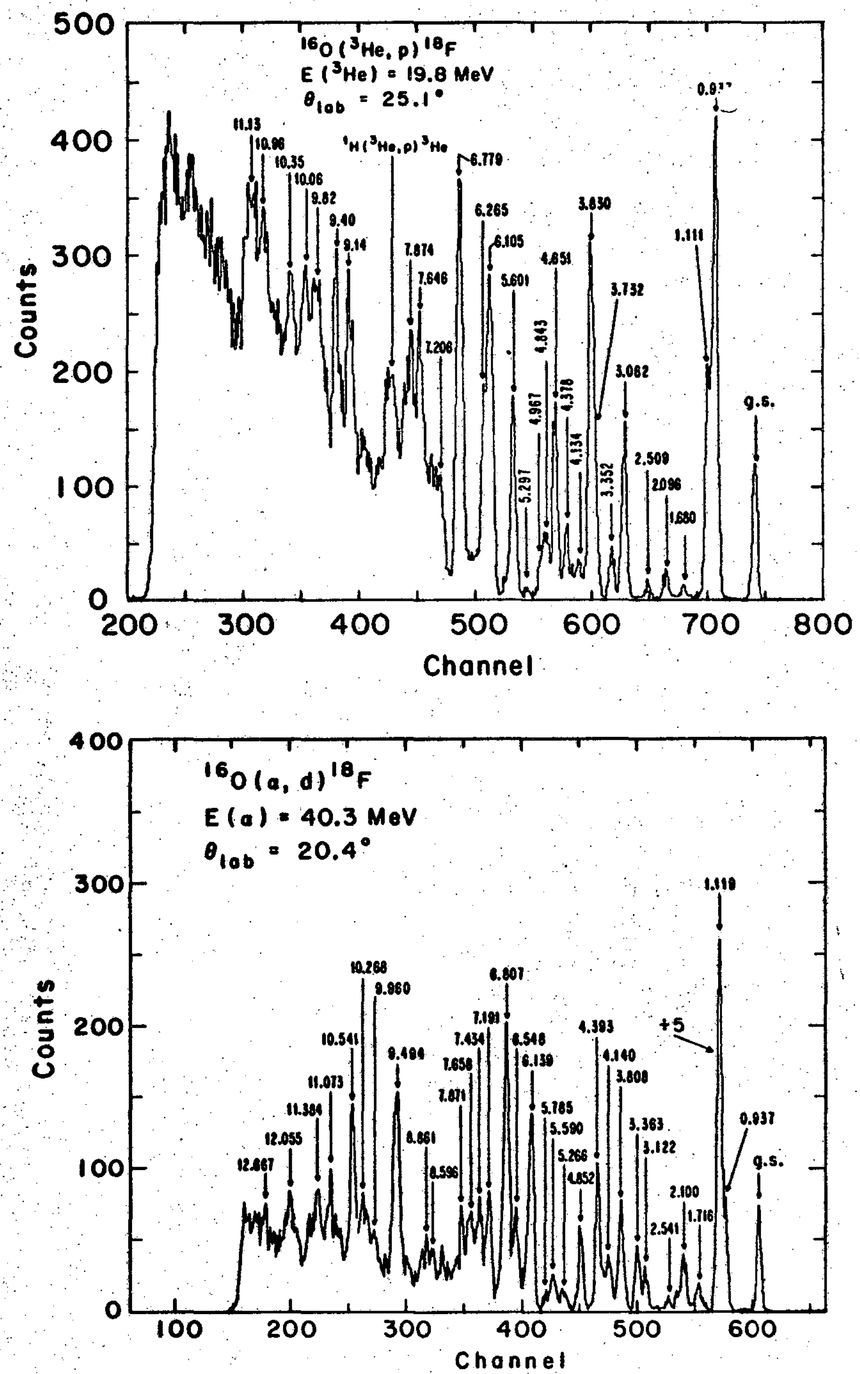
[a] Cross sections integrated from 10° to 82° center of mass. The theoretical cross sections in each column are in proper relative proportion to each other, but have been arbitrarily normalized.

[b] a,b refer to the 1st and 2nd $J^{\pi}t$ theoretical level respectively.

[c] V = real well depth of the ^{3}He optical model potential.

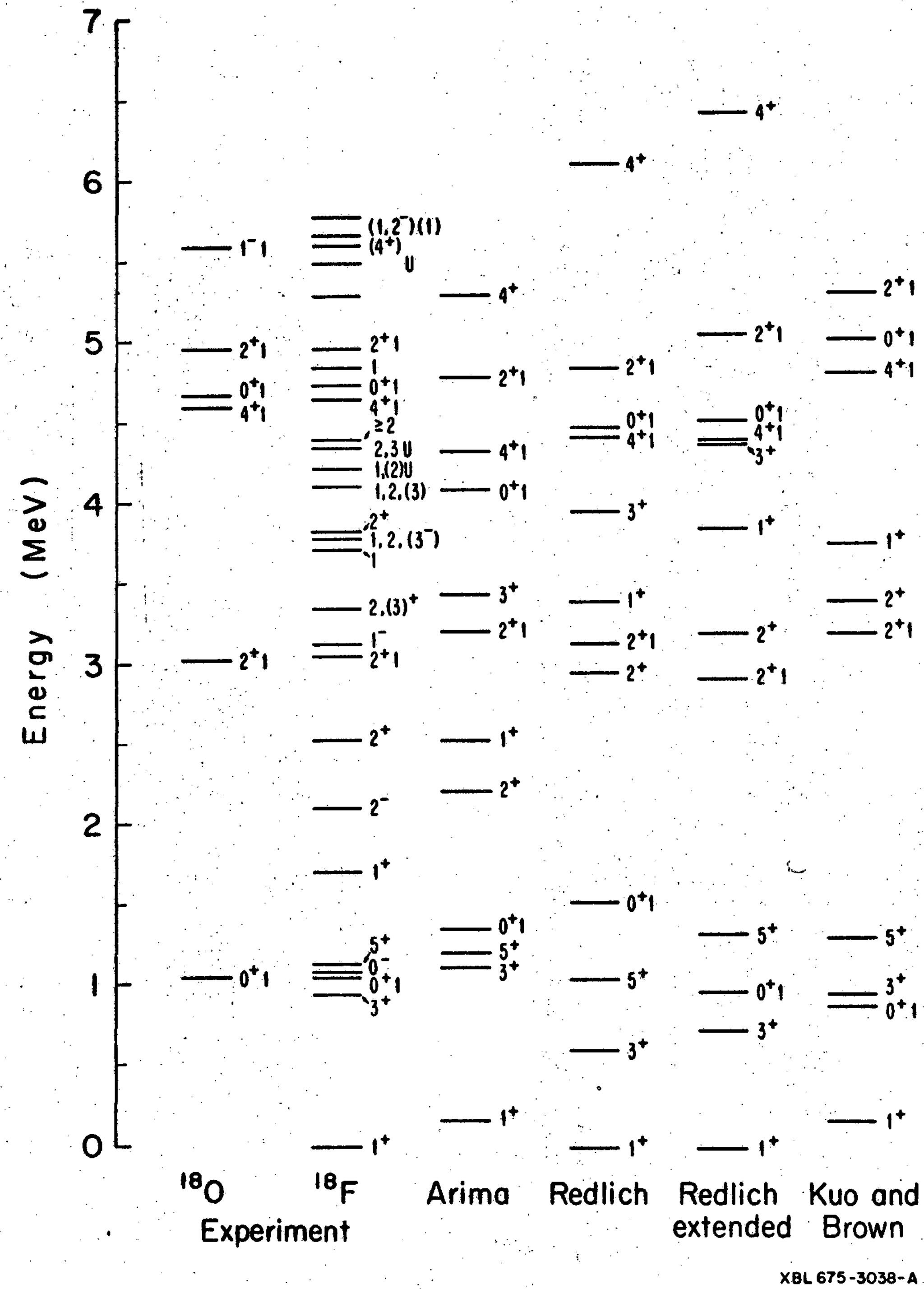
[d] Wave function references are as follows: Arima[41] Kuo and Brown[19] and Redlich.[42,43]

[e] Goodness of fit parameter defined in text. Calculations for 2.524-MeV level not included.



XBL 678-4497

Fig. 1.



Energy (MeV)
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5
4
3
2
1
0
1⁻1
2⁺1
0⁺1
4⁺1
2⁺1
0⁺1
(1,2⁻)(1)
(4⁺)
U
2⁺1
1
0⁺1
4⁺1
≥2
2,3 U
1,(2)U
1,2,(3)
2⁺
1,2,(3⁻)
1
2,(3)⁺
1⁻
2⁺1
2⁺
2⁻
1⁺
5⁺
0⁻
0⁺1
3⁺
1⁺
4⁺
2⁺1
4⁺1
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3⁺
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1⁺
2⁺
2⁺1
5⁺
3⁺
0⁺1
1⁺
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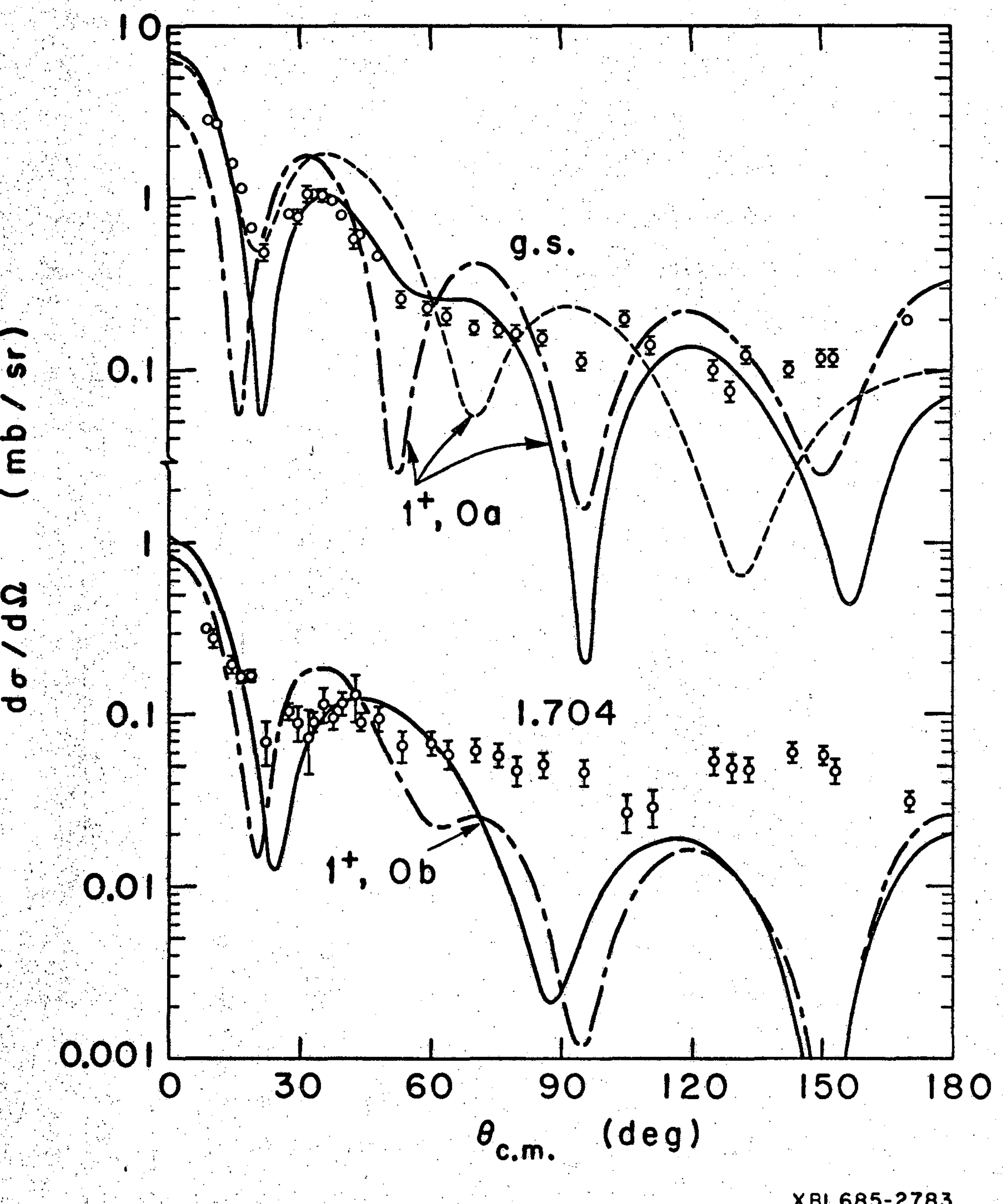
¹⁸F
Experiment
Arima
Redlich
Redlich extended
Kuo and Brown
XBL 675-3038-A

Fig. 2.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1+, 0b
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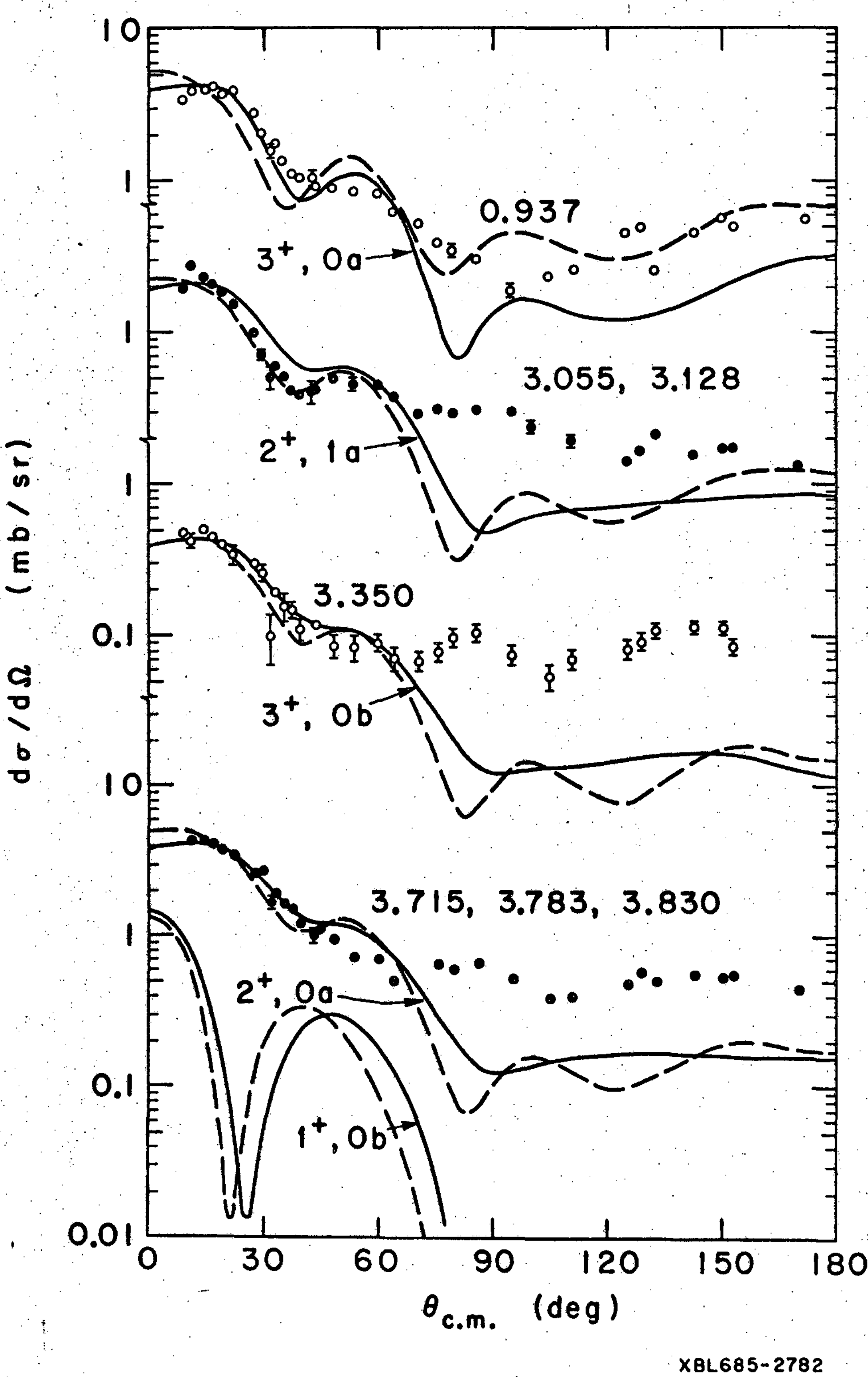
150
180
θc.m. (deg)
XBL685-2783

Fig. 3.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3.350
3⁺, 0b
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1⁺, 0b
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dσ/dΩ (mb/sr)
θc.m. (deg)
XBL685-2782

Fig. 4.

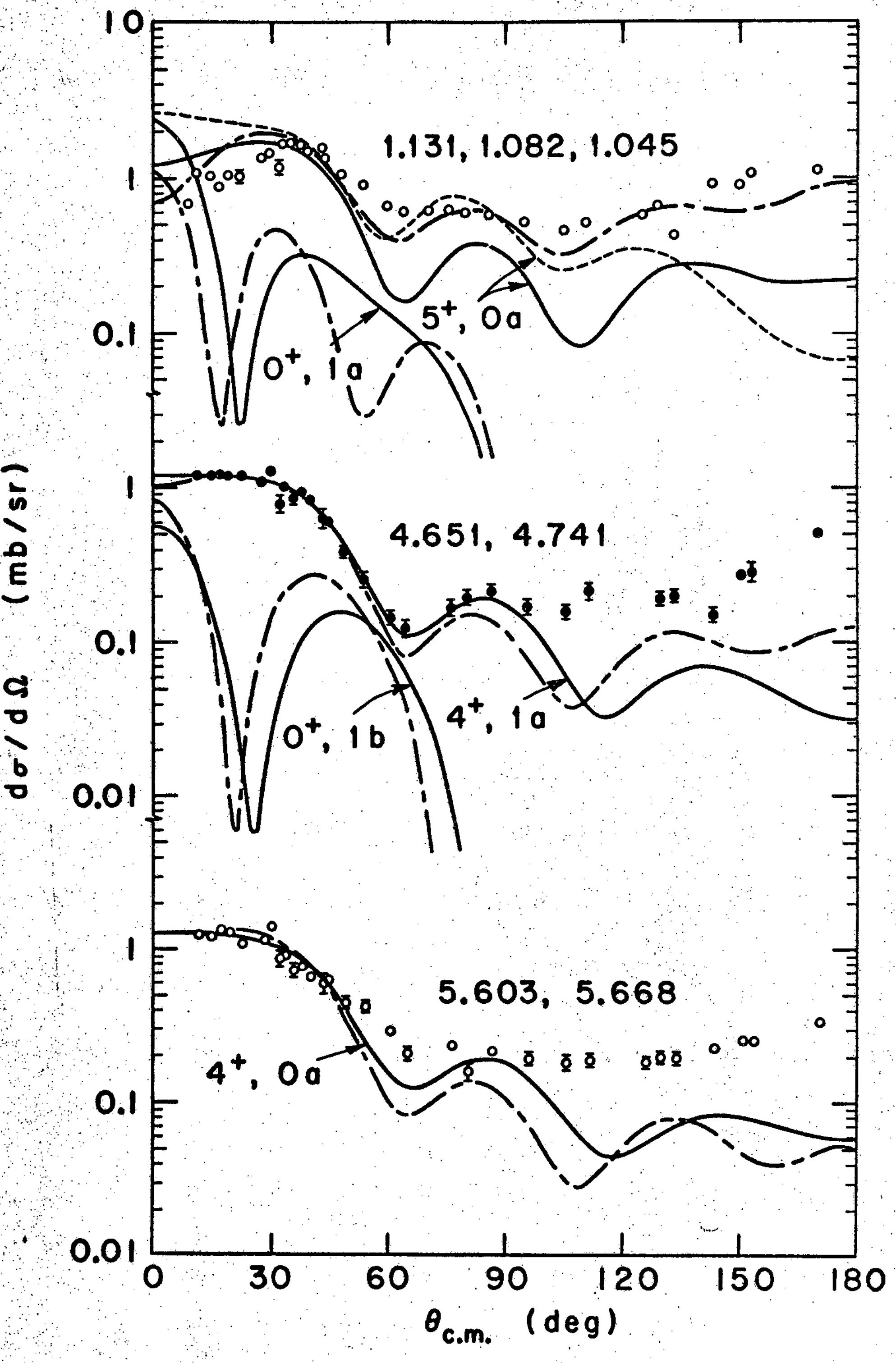

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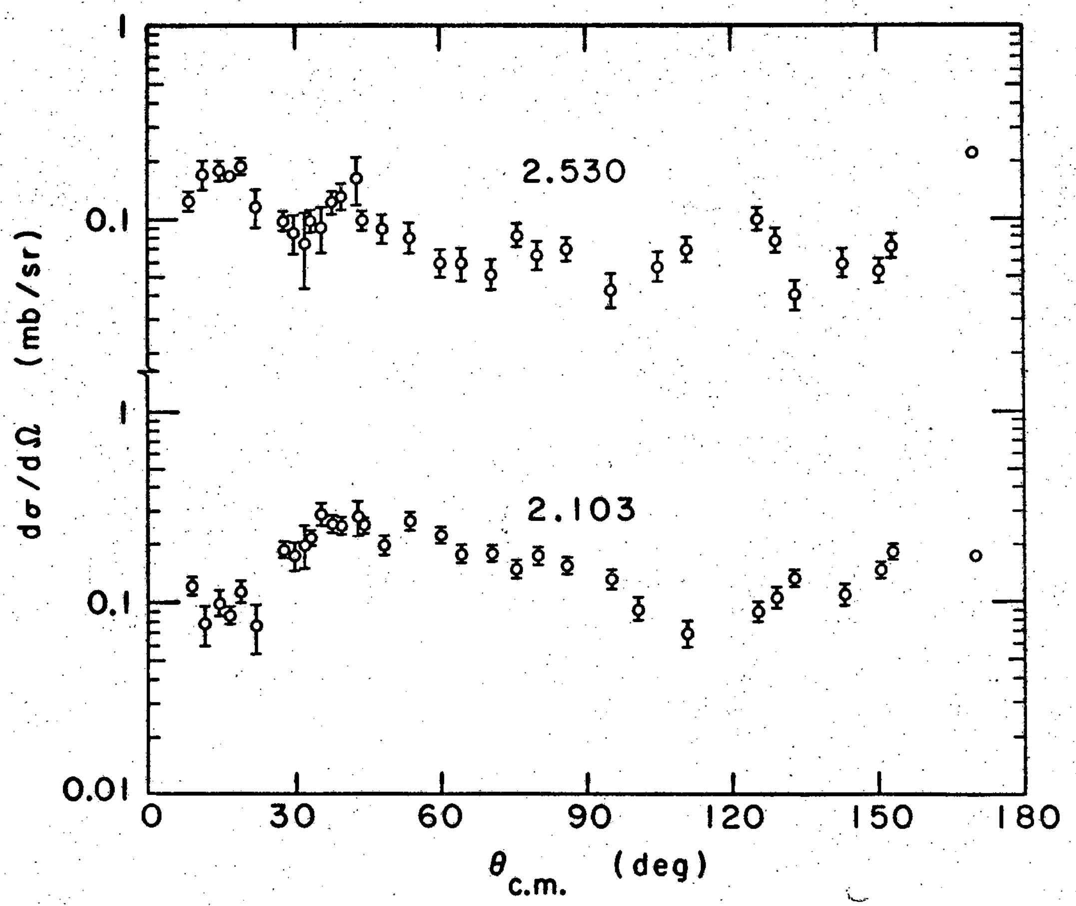
Fig. 5.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60
90
120
150
180
dσ/dΩ (mb/sr)
θc.m. (deg)
XBL675-3039

Fig. 6.