APPENDIX

The relevant information about the decay of Au^{195} is contained in P_i, P_i^K/P_i, P_{co}, and α_{K99}. These quantities are related to the experimental singles and coincidence rates N_k and N_i^j by the equations listed below.

$$N_{130}/N_{31}=[P_{co}^{130}/(1-P_{co}^{130})][(1+\alpha_{31})/(1+\alpha_{130})][\epsilon_{130}/\epsilon_{31}], \tag{A1}$$

$$N_x^{130}/N_{130}=(P_2^K/P_2)\epsilon_x\Omega_2\omega_K, \tag{A2}$$

$$N_x^x/N_{99}^x=2\alpha_{K99}[\epsilon_x/\epsilon_{99}][1+A], \tag{A3}$$

$$A=\frac{(P_2^K/P_2)P_{co}^{130}[\alpha_{K130}/(1+\alpha_{130})][(1+\alpha_{99})/\alpha_{K99}]}{(P_2^K/P_2)(1-P_{co}^{130})+(P_3^K/P_3)(P_3/P_2)},$$

$$N_{99}/N_{130}=[(1-P_{co}^{130})/P_{co}^{130}+P_3/P_2P_{co}^{130}][(1+\alpha_{130})/(1+\alpha_{99})][\epsilon_{99}/\epsilon_{130}], \tag{A4}$$

$$N_x^{99}/N_{99}=[(1-P_{co}^{130})(P_2^K/P_2)+(P_3^K/P_3)(P_3/P_2)]\epsilon_x\Omega_2\omega_K/[(1-P_{co}^{130})+P_3/P_2], \tag{A5}$$

$$N_x/N_{130}=[P_2^K/P_2+P_{co}\alpha_{K130}/(1+\alpha_{130})+(1-P_{co}^{130})\alpha_{K99}/(1+\alpha_{99})+P_3/P_2[P_3^K/P_3+\alpha_{K99}/(1+\alpha_{99})]$$
$$+(P_4^K/P_4)(P_4/P_2)]\omega_K(\epsilon_x/\epsilon_{130})(1+\alpha_{130})/P_{co}^{130}, \tag{A6}$$

$$N_{210}/N_{130}=[(P_1/P_2)(P_{co}^{210}/P_{co}^{130})][(1+\alpha_{130})/(1+\alpha_{210})](\epsilon_{210}/\epsilon_{130}). \tag{A7}$$

In all these expressions it was assumed that the 130-keV state is formed mainly in the decay of Au^{195} via the P_2 branch. This assumption is justified by the fact that within this approximation $P_1/P_2\leqslant 10^{-2}$ for $P_{co}^{210}\geqslant 0.1$.

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$B^{11}(d,p)B^{12}$ Angular Distributions at $E_d=5.5$ MeV for the B^{12} 2.62- and 2.72-MeV Levels

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The angular distributions of the $B^{11}(d,p)$ B^{12} reaction leading to the 0.95-, 1.67-, 2.62-, 2.72-MeV levels of B^{12} were measured at an incident deuteron energy of 5.5 MeV. The angular distribution of the elastically scattered deuterons from B^{11} was also measured. The results were analyzed both by Butler theory and by zero-range distorted-wave Born-approximation calculations. The orbital angular momentum transferred in the reaction was determined to be $l_n=1$, 0, 0, and (1) for these states of B^{12}. Some $B^{11}(d,p\gamma)$ B^{12} measurements were made. The results for the decay of the 1.67-, 2.62-, and 2.72-MeV states were consistent with previous work. The 3.39-MeV level of B^{12} was found to have a partial width for gamma decay which is less than 10% of the total width. The level structure of B^{12} is compared with the spectrum of C^{12} above 15-MeV excitation. Recent $B^{11}(d,p)$ B^{12} angular-distribution measurements of Mingay are used to analyze Doppler-shift measurements of Warburton and Chase for the B^{12} 1.67- and 2.62-MeV levels. The result is limits of less than 10^{-13} sec on the mean lifetimes of both states.

I. INTRODUCTION

THERE have been numerous investigations[1–8] of the angular distributions of the $B^{11}(d,p)B^{12}$ reaction ($Q=1.145$ MeV) leading to various bound states of B^{12}. The angular distributions for the ground state and first two excited states in the energy region investigated are all indicative of a direct reaction mechanism and have been analyzed by either the plane-wave Born

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approximation (Butler theory) or distorted-wave Born approximation (DWBA). These results lead to unambiguous assignments of $l_n=1$, 1, and 0 for the angular distributions leading to the B^{12} ground state and first and second excited states at 0.95 and 1.67 MeV. These assignments combined with other results[9] lead to an assignment of $J^\pi=1^+$ for the ground state, to $J^\pi=2^+$ for the 0.95-MeV level[10], and to $J^\pi=2^-$ for the 1.67-MeV level.[11] The only other known bound levels of B^{12} are those at excitation energies of 2.62 and 2.72 MeV.[9] Assignment of the orbital-angular-momentum transfer l_n in the $B^{11}(d,p)B^{12}$ reaction has proven to be difficult for these two levels, especially the 2.72-MeV level. On the experimental side, good resolution is demanded to separate the proton groups leading to these two levels, and the Q values -1.475 and -1.575 MeV are such that for a large part of the angular range of observation the deuteron group from $B^{11}(d,d)B^{11}$ has approximately the same energy as these proton groups. On the theoretical side there is the difficulty that the predicted plane-wave angular distributions for $l_n=0$ and 1 are quite similar for these two levels at deuteron energies of sufficient energy to enable the proton groups to be detected and to ensure the predominance of the stripping mechanism.

The cross section for formation of the 2.62-MeV level is considerably larger than that for the 2.72-MeV level so that the angular distribution for the unresolved doublet is essentially that of the 2.62-MeV level. The angular distribution of the unresolved doublet was previously measured[3] using a deuteron energy of 5.5 MeV, and Butler theory was used in the analysis of the results. It was found with this theory that $l_n=0$ and $l_n=1$ gave equally acceptable fits to the angular distribution (assumed to represent the 2.62-MeV level alone). However, neither fit was especially good—indicating some distortion effects and/or a non-negligible contribution from the 2.72-MeV level.

The work reported on here is a further measurement of the $B^{11}(d,p)B^{12}$ angular distributions at $E_d=5.5$ MeV using energy resolution sufficient to separate the proton groups corresponding to the 2.62- and 2.72-MeV levels and using DWBA analysis of these distributions. In addition, the angular distribution of elastic deuteron scattering was measured as an aid to the DWBA analysis. We also give a brief description of measurements and analysis of (p,γ) coincidence experiments on the $B^{11}(d,p\gamma)B^{12}$ reaction.

II. ANGULAR DISTRIBUTIONS FOR THE $B^{11}(d,p)B^{12}$ REACTION

A. Experimental Procedure and Results

All of our work was done using the Strasbourg Center of Nuclear Research 5.5-MeV Van de Graaff accelerator. The angular distributions of the elastically scattered deuterons and the proton group (p_1) corresponding to the B^{12} 0.95-MeV level were measured using silicon-surface-barrier counters to detect the charged particles. The target was an evaporated self-supporting foil of enriched B^{11}, 50 $\mu g/cm^2$ thick. Spectra were recorded with a 400-channel analyzer at reaction angles between 8° and 160° with a monitor counter fixed at 90° to the beam. Various aluminum foils with thicknesses between 0.05 and 0.17 mm were placed in front of the charged-particle counter in order to change the relative energies of protons, deuterons, and α particles.

A charged-particle spectrum for $E_d=5.5$ MeV recorded at an angle to the beam of 90° with a 0.11-mm Al foil in front of the detector is shown in Fig. 1. The proton and deuteron groups assigned to carbon and oxygen isotopes arise from carbon and oxygen contamination of the target. The broad group on the low-energy side of the O^{17} ground-state group is the α_0 group from the $B^{11}(d,\alpha)Be^9$ reaction ($Q=8.027$ MeV).

The angular distribution of the $B^{11}(d,d)B^{11}$ reaction extracted from spectra of this sort is shown in Fig. 2. No points are shown for angles less than 55° since the elastic peaks of B^{11}, C^{12}, and O^{16} were not separated for these angles. The solid line shown in Fig. 2 will be discussed in Sec. IIB.

The angular distribution of the $B^{11}(d,p)B^{12}$ (0.95-MeV level) reaction is illustrated in Fig. 3. The solid line is a smooth curve drawn through the experimental points. The dashed curve is the Butler theory for $l_n=1$ and $R=4.5$F. It is seen that the Butler curve gives a good description of the forward peak but not of the differential cross section for angles greater than 60°.

The absolute cross-section scale of Fig. 3 was obtained relative to the absolute cross section measured for the $B^{11}(d,p)B^{12}$ (0.95-MeV level) by Pullen *et al.*[5] at $E_d=3.0$ MeV by measuring the 90° relative intensities of the B^{11} p_1 group at $E_d=3.0$ and 5.5 MeV. Absolute cross sections for the other levels of B^{12} and the $B^{11}(d,d)B^{11}$ reaction were obtained relative to that for the 0.95-MeV level. All of the measured absolute cross sections are assigned an uncertainty of $\pm 15\%$.

The angular distributions of the (d,p) reaction leading to the B^{12} 1.67-, 2.62-, and 2.72-MeV levels were measured using a Buechner-type 40-cm radius broad-range magnetic spectrograph. The spectrograph scattering chamber was not equipped with an accurate beam integrator or reaction-particle monitor so that the angular distributions were obtained by normalizing to the angular distribution of the $B^{11}(d,p)B^{12}$ (0.95-MeV level) re-

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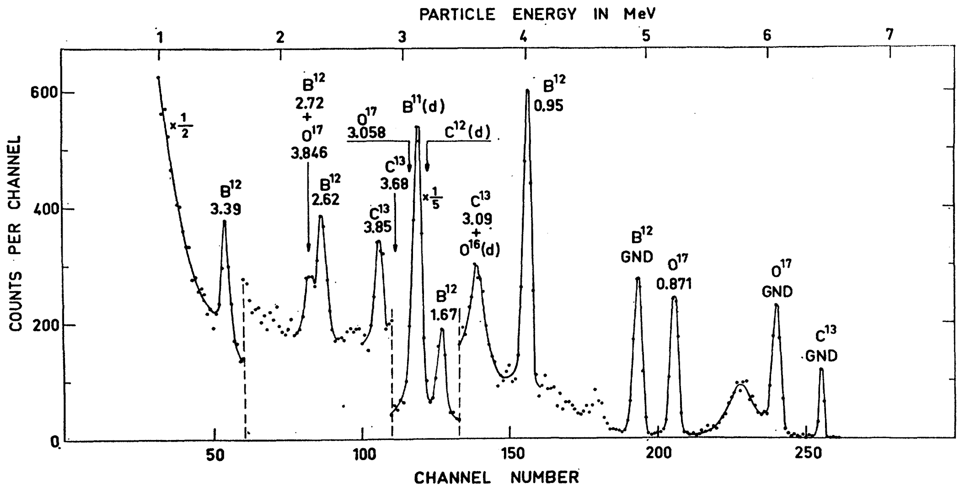

FIG. 1. Charged-particle spectrum from a 50 $\mu g/cm^2$ self-supporting target of enriched B^{11} bombarded by a 5.5-MeV deuteron beam. The spectrum was recorded at 90° to the beam by a silicon-surface-barrier detector covered by a 0.11-mm Al foil. The proton peaks are identified by the nucleus and excitation energy (MeV) to which they are assigned. The elastically scattered peaks are also labelled.

action, i.e., the solid curve of Fig. 3. Spectra were recorded at reaction angles between 10° and 126°. The 20° proton spectrum for proton energies between 2.9 and 6.5 MeV is shown in Fig. 4, and the angular distributions for the reactions leading to the 1.67-, 2.62-, and 2.72-MeV levels are shown in Figs. 5, 6, and 7. Some of the experimental points for the 1.67-MeV level distribution (Fig. 5) were obtained from the silicon-detector spectra (e.g., Fig. 1). The angular distributions of the reactions leading to the 0.95-, 1.67-, and 2.62-MeV levels are in good agreement with previous measurements[2,3] made at this laboratory with $E_d = 5.5$ MeV but cover a wider range of angles.

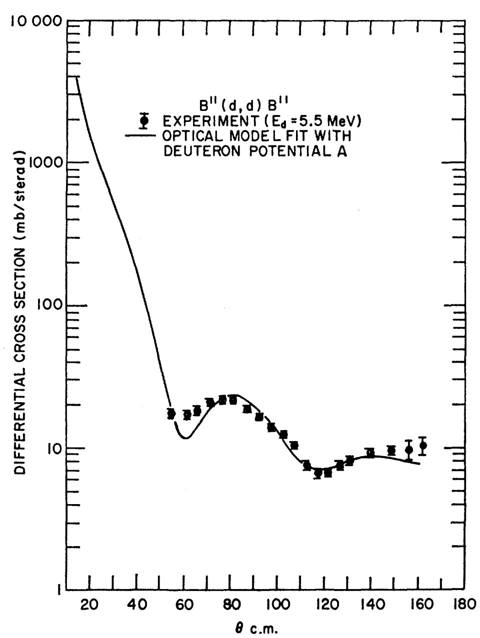

FIG. 2. Differential cross section for the elastic scattering of 5.5-MeV deuterons by B^{11}. The optical-model fit is explained in the text.

It is seen that the Butler theory for $l_n = 0$ provides a good description of the 1.67-MeV level distribution (Fig. 5) as it does at other bombarding energies.[1,2,4,5,8] The main purpose of this work was to assign l_n values to the distributions leading to the 2.62- and 2.72-MeV levels. We see from Figs. 6 and 7 that the 2.62-MeV level distribution is best fitted with $l_n = 0$ and the 2.72-MeV level distribution is best fitted with $l_n = 1$ if we use the radius parameter $R = 4.5$ F which best fits the 0.95-MeV and 1.67-MeV level distributions. These fits are just about as good as the respective $l_n = 0$ fit of Fig. 5 and the $l_n = 1$ fit of Fig. 3; however, the 2.62-MeV level can be fitted equally well by $l_n = 1$ with $R \approx 8$ F, and the 2.72-MeV level can be fitted equally well by $l_n = 0$ and a small value of R or $l_n = 2$ and a larger value of R.

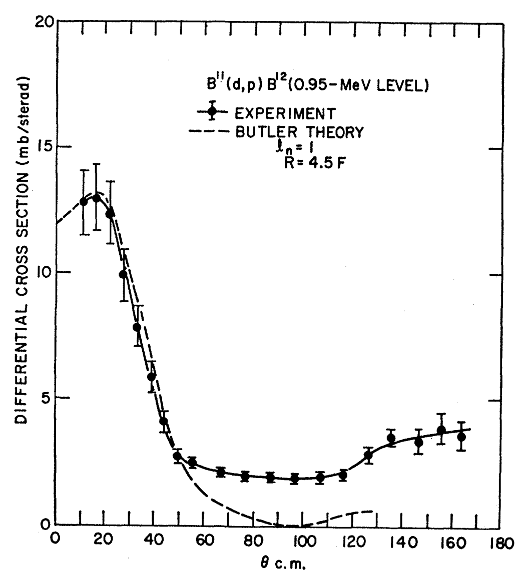

FIG. 3. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (0.95-MeV level) at $E_d = 5.5$ MeV compared with the Butler theory for $l_n = 1$ and $R = 4.5$F which has been normalized to the peak experimental cross section.

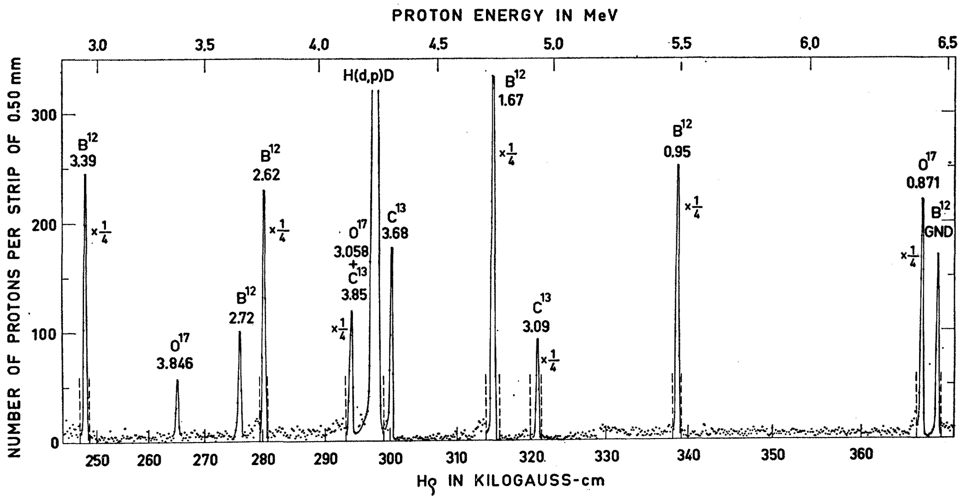

FIG. 4. Proton spectrum from a 50 $\mu g/cm^2$ self-supporting target of enriched B^{11} bombarded by a 5.5-MeV deuteron beam. The spectrum was recorded using photographic-plate detection at 20° to the beam in a broad-range magnetic spectrograph. The proton groups are identified by the nucleus and excitation energy (MeV) to which they are assigned.

After this work was completed we found that the angular distribution of the $B^{11}(d,p)B^{12}$ (2.62-MeV level) reaction had been measured recently at $E_d = 3$ MeV[4,8] and at $E_d = 4$ MeV.[4] At both these energies the same ambiguity between $l_n = 0$ and $l_n = 1$ was encountered as is described here.

A measurement of the angular distribution leading to the 2.72-MeV level has not been reported previously. At first sight it is rather surprising that this distribution shows as clear a stripping pattern as that for the 0.95-MeV level even though the cross section is about 15 times smaller.

In the next subsection we describe the procedure used to analyze the angular distributions with the DWBA theory in a more detailed attempt to assign l_n values to the distributions leading to the B^{12} 2.62- and 2.72-MeV levels.

B. Distorted-Wave Calculations

The angular-momentum transfers in the transitions to the states at 2.62 and 2.72 MeV may be determined

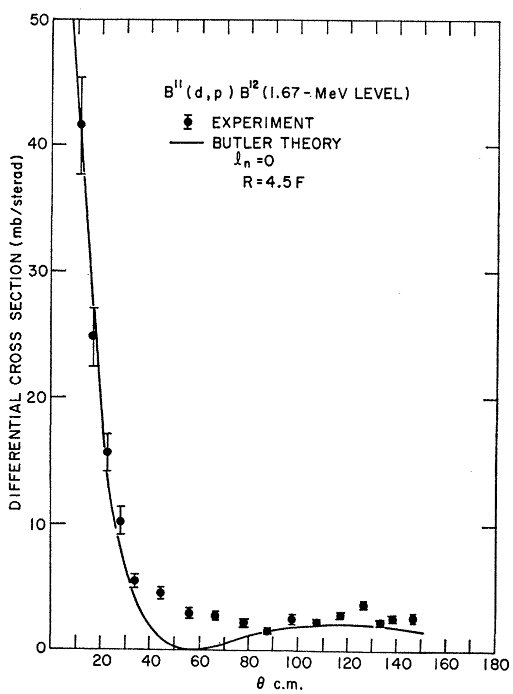

FIG. 5. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (1.67-MeV level) at $E_d = 5.5$ MeV compared with the Butler theory for $l_n = 0$ and $R = 4.5$F which has been normalized to the peak experimental cross section.

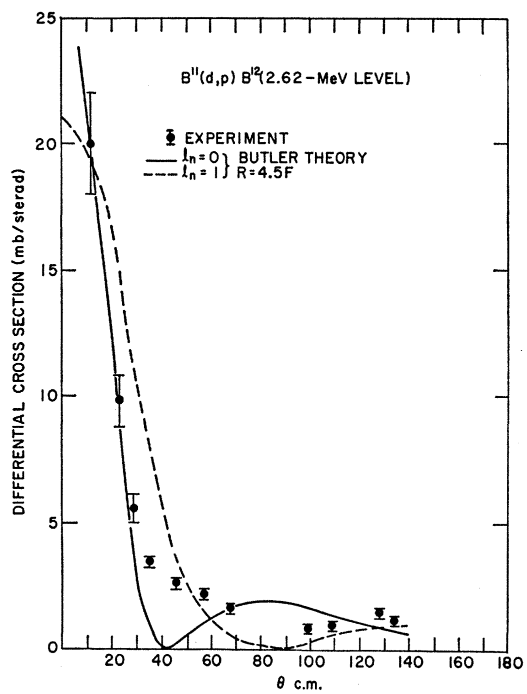

FIG. 6. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (2.62-MeV level) at $E_d = 5.5$ MeV compared with the Butler theory for $R = 4.5$F and $l_n = 0$ and 1. The theoretical curves have been normalized to the peak experimental cross section.

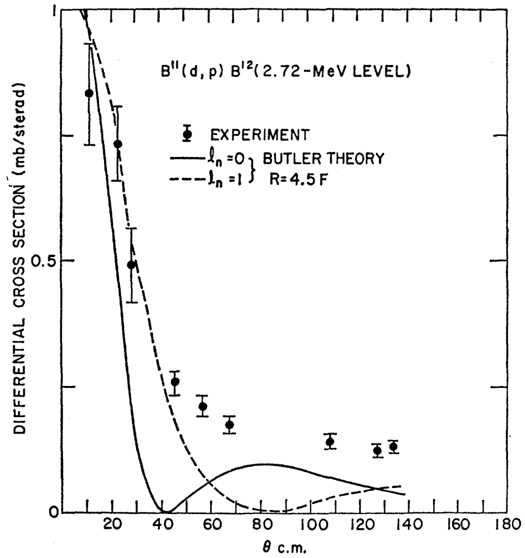

FIG. 7. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (2.72-MeV level) at $E_d=5.5$ MeV compared with the Butler theory for $R=4.5$F and $l_n=0$ and 1. The theoretical curves have been normalized to the experimental cross section at forward angles.

by making distorted-wave calculations of the differential cross section for the stripping reaction with various assumed values of the angular-momentum transfer and comparing with the measured cross sections. The distorted waves are generated by the optical potentials that fit the corresponding elastic-scattering data. Normally this calculation is straightforward, but in the present case some uncertainty is introduced by the lightness of the target nucleus. In such cases the optical model may not be applicable, so that it is either not possible to obtain a fit to the elastic-scattering data or, if a fit is obtainable, it is only with parameters that may be considered somewhat unphysical or do not vary smoothly with energy or mass number, as they do for medium and heavy nuclei. It is therefore necessary to study the sensitivity of the calculated cross sections to variations in the optical potentials, and to verify that the method gives the correct result in cases where it is already known.

The measured differential cross section for the elastic scattering of deuterons by B^{11} was fitted by an optical potential of the form,

$$V(r)=V_c(r)+Uf(r)+iWg(r),$$

where $V_c(r)$ is the Coulomb potential, U and W are the depths of the real and imaginary potentials, and $f(r)$ and $g(r)$ are Saxon-Woods and surface Gaussian form factors given by $f(r)=[1+\exp\{(r-r_0A^{1/3})/a\}]^{-1}$ and $g(r)=\exp[-\{(r-r_WA^{1/3})/b\}^2]$. No spin-orbit potentials were included as they are unlikely to affect the final result significantly. The fitting was done by an automatic parameter-search routine[12,13]; the fit obtained is shown by the solid curve in Fig. 2, and the parameters of the optical potential (deuteron A) are given in Table I. It was not possible to obtain a satisfactory fit using the optimum form factors of Perey and Perey.[14] The wave functions of the captured neutrons in the subsequent DWBA calculations were calculated for Saxon-Woods wells with $r_0=1.25$ F, $a=0.65$ F, and depths adjusted to give the experimental binding energies.

TABLE I. Optical potentials for protons of 5.5–8 MeV and deuterons of 5.5 MeV elastically scattered by boron.

Potential[a]	U	r_U	a	W	r_W	b
Proton	54	1.25	0.65	7.0	1.25	0.98
Deuteron A	109	0.674	1.225	39.51	2.065	0.813
Deuteron B	77	1.15	0.81	29.8	1.37	1.42

[a] Potentials are in MeV and size parameters in F.

No corresponding data for proton scattering are available, so the typical proton potential given in Table I was used. Several calculations showed that the final (d,p) cross section is insensitive to the parameter values chosen (see Fig. 8).

These deuteron and proton potentials were used in zero-range DWBA calculations of the $B^{11}(d,p)B^{12}$ stripping cross section to the 0.95- and 1.67-MeV states of B^{12} for angular momentum transfers of 0, 1, and 2 in

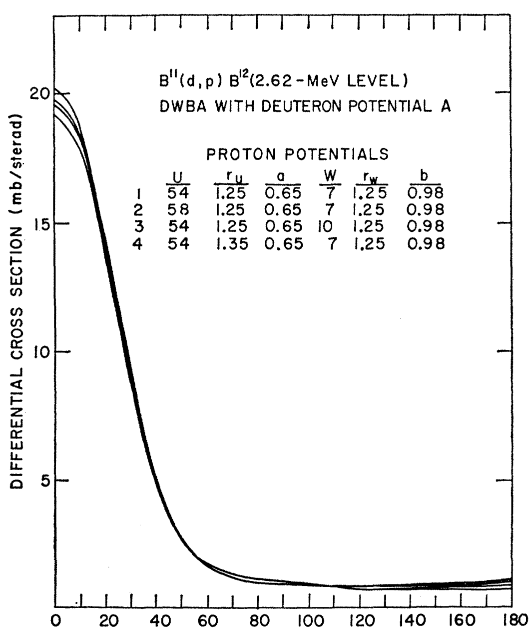

FIG. 8. Distorted-wave calculations of the differential cross section for the reaction $B^{11}(d,p)B^{12}$ (2.62-MeV level) showing the insensitivity to the proton optical potential. Since the four curves are practically indistinguishable they are not labelled.

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each case. The results are shown in Figs. 9 and 10. The comparison of the DWBA calculation with the data for the 2.62- and 2.72-MeV levels is shown in Fig. 11. The curve for $l_n=1$ is normalized to the average of the two points at the peak of the 2.72-MeV distribution. It is seen that the $l_n=0$ DWBA curve gives an excellent description of the angular distribution for the 2.62-MeV level, while $l_n=1$ and 2 give poor fits. For the 2.72-MeV level, $l_n=1$ gives as good a fit as it did to the 0.95-MeV level, while $l_n=0$ and 2 give inferior fits at the forward peak. The conclusions drawn from the DWBA calculations for these two levels, then, are essentially the same as they were for the Butler theory results with $R=4.5$ F.

It is desirable to verify that the conclusions from the DWBA calculations are not unduly dependent on the

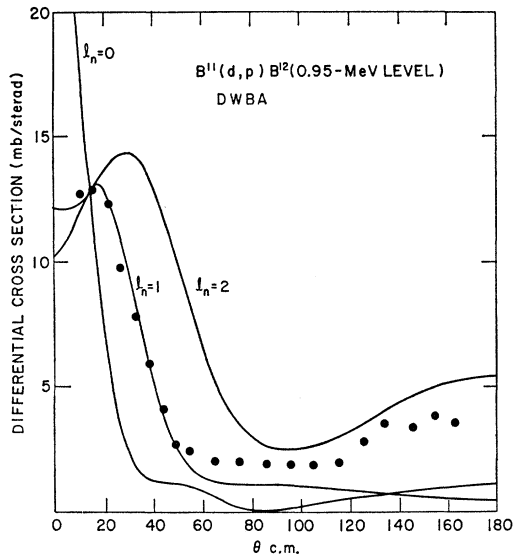

FIG. 9. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (0.95-MeV level) at $E_d=5.5$ MeV compared with the distorted-wave calculations with deuteron potential A and $l_n=0$, 1, and 2. The error bars have been omitted from the experimental points. All three curves have been normalized to the peak of the experimental distribution.

deuteron potential, so calculations were also made with a potential fitted to the data of Pullen[5] on the elastic scattering of 3-MeV deuterons by B^{10}. This is called deuteron potential B, and is given in Table I. The results of DWBA calculations with deuteron potential A and B are shown in Figs. 12 and 13 for the 0.95- and 1.67-MeV levels, respectively. It is found that though there are appreciable differences between the cross sections, the identifications of the angular-momentum transfers in the transitions are not altered. This was also true for the 2.62- and 2.72-MeV levels for which potentials A and B give practically identical results.

We conclude that the 2.62-MeV level almost certainly is formed by the capture of $l_n=0$ neutrons, and thus has $J^\pi=1^-$ or 2^-. Since the same conclusion is reached from analysis of results for $E_d=3$ MeV[4,8] and 4 MeV,[4] a defi-

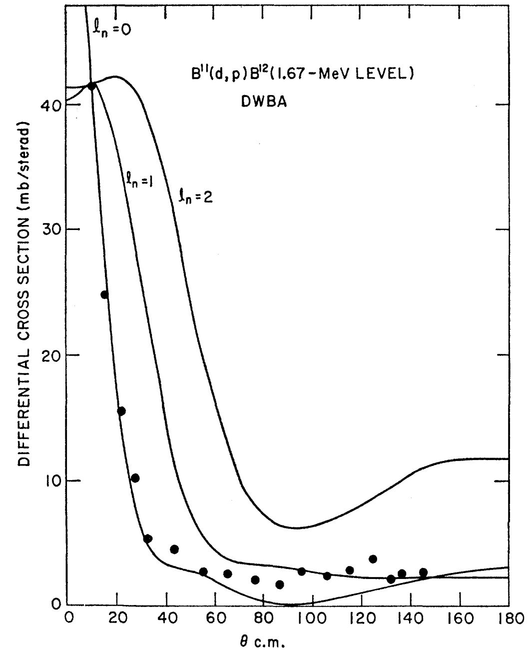

FIG. 10. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (1.67-MeV level) at $E_d=5.5$ MeV compared with the distorted-wave calculations for deuteron potential A and $l_n=0$, 1, and 2. The error bars have been omitted from the experimental points. All three curves have been normalized to the maximum experimental cross section.

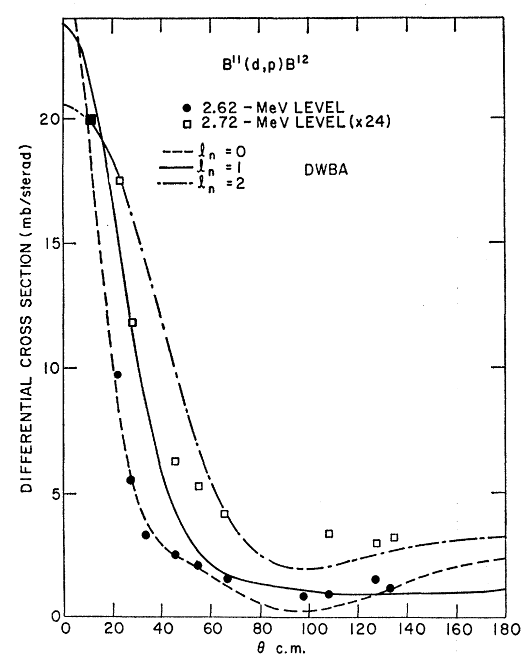

FIG. 11. Differential cross sections for the reactions $B^{11}(d,p)B^{12}$ (2.62-MeV level) and $B^{11}(d,p)B^{12}$ (2.72-MeV level) at $E_d=5.5$ MeV compared with the distorted-wave calculations for deuteron potential A and $l_n=0$, 1, and 2. The error bars have been left off the experimental points, and the experimental cross section for the reaction $B^{11}(d,p)B^{12}$ (2.72-MeV level) has been multiplied by 24. The theoretical curves have been arbitrarily normalized.

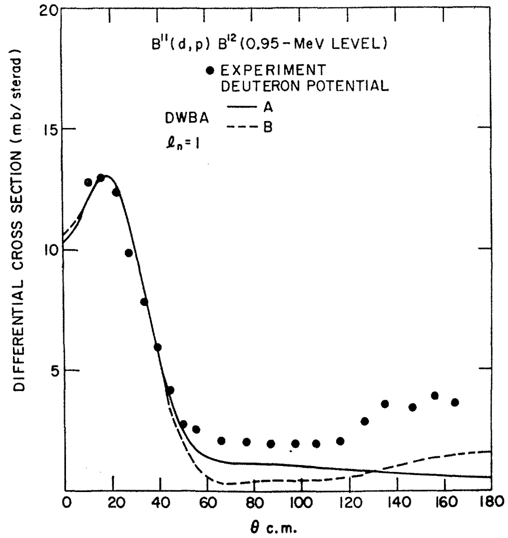

FIG. 12. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (0.95-MeV level) at $E_d=5.5$ MeV compared with the distorted-wave calculations for $l_n=1$ and deuteron potentials A and B.

nite assignment of 1^- or 2^- can be made from stripping analysis. Combining this result with the $B^{11}(d,p\gamma)B^{12}$ angular correlation results,[11] results in an assignment of $J^\pi=1^-$ to the B^{12} 2.62-MeV level.

The best fit to the angular distribution leading to the B^{12} 2.72-MeV level is for $l_n=1$; however, we do not feel that $l_n=0$ or 2 can be excluded with absolute certainty especially since the quite low cross section allows the possibility of a sizeable contribution from compound-

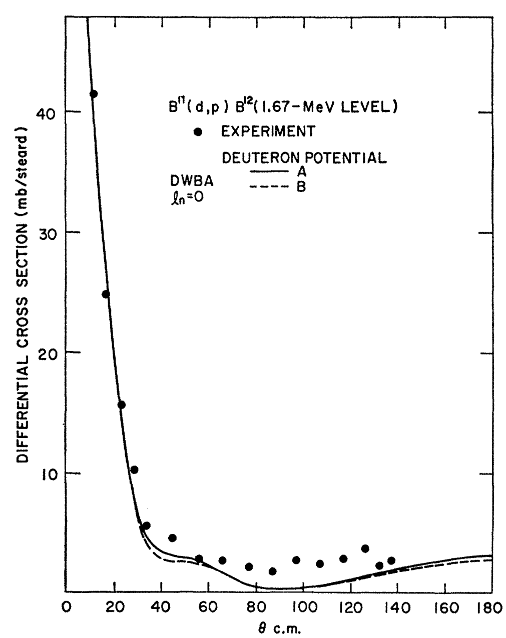

FIG. 13. Differential cross section for the reaction $B^{11}(d,p)B^{12}$ (1.67-MeV level) at $E_d=5.5$ MeV compared with the distorted-wave calculations for $l_n=0$ and deuteron potentials A and B.

nucleus formation. The allowable spin-parity assignments for the B^{12} 2.72-MeV level for $l_n=1$ are $J^\pi \leqslant 3^+$, and this choice we take as most probable.

The spectroscopic factors $S=[\sigma(\exp)/\sigma(\text{theory})$ at peak] corresponding to the DWBA calculations for deuteron potentials A and B are listed in Table II. Also listed are spectroscopic factors for the Butler theory with $R=4.5$ F for the present work and $R=4.4$ F for the previous results of Holt and Marsham[1,15] at $E_d=8$ MeV. For this theory the spectroscopic factor has the form $S=\Theta^2/\Theta_0^2$, where Θ^2 is the Butler-theory reduced width of the state and Θ_0^2 the single-particle reduced width.[15] We take Θ_0^2 to be 0.10 and 0.05 for $l_n=0$ and 1, respectively. These numbers are somewhat arbitrary but seem consistent with other work[15] for the kinematics involved. In view of the difficulties of applying the optical model to light nuclei, the values of S extracted from the DWBA theory are only of qualitative accuracy. Bearing this in mind, it is still encouraging that deuteron potentials A and B give relative spectroscopic factors for the four levels which are consistent with each other. It appears from these results that the B^{12} 1.67- and 2.62-MeV levels have roughly equal values of S and that both levels have the B^{11} ground state as their major parent.

The spectroscopic factors extracted from the Butler-theory analysis of the $E_d=8$-MeV data[1] are 50% larger than for the $E_d=5.5$-MeV data. This can be qualitatively explained as due to the neglect of the Coulomb potential by this theory, since the suppression of the cross section by the Coulomb potential is expected to be appreciably more severe at the lower incident energy.

All the DWBA calculations were made on the Aldermaston Stretch Computer using the program written by Macefield[16] following the formalism of Buck and Hodgson.[17]

III. $B^{11}(d,p\gamma)B^{12}$ COINCIDENCE MEASUREMENTS

The motive for studying (p,γ) coincidences was to search for the ground-state decay of the 2.62-MeV level and to obtain what information was possible on the decay modes of the 2.72- and 3.39-MeV levels. Previous information on the decay of the 2.62- and 2.72-MeV levels was that these two levels have ground-state branches of $<13\%$[11] and $>80\%$[18], respectively. For a $J^\pi=1^-$ assignment to the 2.62-MeV level an $E1$ transition to the ground state is expected while significant cascades to the 0.95- and/or 1.67-MeV levels would appear probable for the 2.72-MeV level unless it has $J^\pi=0^+$. The 3.39-MeV level is about 20 keV above the $B^{11}+n$ threshold.[6] Nothing is known about its decay modes.

[15] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).
[16] B. E. F. Macefield (private communication).
[17] B. Buck and P. E. Hodgson, Phil. Mag. **6**, 1371 (1961).
[18] R. R. Carlson and E. Norbeck, Phys. Rev. **131**, 1204 (1963).

TABLE II. Spectroscopic factors $S = [\sigma(\exp)/\sigma(\text{theory})$ at peak$]$ for the reaction $B^{11}(d,p)B^{12}$.

E_x (MeV)	J	l_n	Deuteron potential A	B	Butler theory (a)	(b)
0.95	2	1	0.71	0.58	0.4	0.6
1.67	2	0	0.43	0.34	0.3	0.45
2.62	1	0	0.64	0.51	0.4	···
2.72	0[c]	(1)	0.13	0.08	0.1	···

[a] Present work.
[b] $E_d = 8$ MeV (Refs. 1 and 15).
[c] Assumed value, to obtain S for $J = 1$, 2, or 3 divide by $(2J+1)$.

Two-dimensional analysis of the $B^{11}(d,p\gamma)B^{12}$ reaction was made at $E_d = 5.0$ MeV with the proton counter at 60° to the deuteron beam and a 2-in.×2-in. NaI(Tl) gamma-ray detector at right angles to the reaction plane and 2 cm from the target. A 4096-channel Intertechnique analyzer and standard slow-fast coincidence circuitry were used. Two (p,γ) coincidence spectra were recorded in the study of the 2.62- and 2.72-MeV levels, one lasting 12 h with 32 channels for the proton spectra and 128 channels for the gamma-ray spectra, and one lasting 20 h with 128 channels for the proton spectra and 32 channels for the gamma-ray spectra. The target was a 50 $\mu g/cm^2$ self-supported B^{11} foil. The proton groups leading to the B^{12} 2.62- and 2.72-MeV levels were not resolved in the proton spectra; however, the relative intensities of these two groups were determined from an exposure made with the Buechner magnet using the same thickness target and the same deuteron energy and reaction angle. The result of this measurement was approximately 10:1 for the intensity ratio of the proton groups leading to the 2.62- and 2.72-MeV levels.

The results obtained from analysis of the (p,γ) coincidence spectra were in good agreement with previous results.[11,18] The second excited state at 1.67 MeV was found to decay predominantly to the ground state with a $1.67 \rightarrow 0.95$ branch of less than 10%. This branch was previously found[11] to be $(3\pm1)\%$. The 2.62-MeV level was found to decay predominantly by emission of gamma rays of 0.95 and 1.67 MeV with a $(9\pm6)\%$ ground-state transition; while the 2.72-MeV level was found to decay predominantly (>60%) by a ground-state transition. Thus, the only new information provided by this work is the slight evidence for a weak $(9\pm6)\%$ ground-state branch from the 2.62-MeV level.

The study of the decay of the B^{12} 3.39-MeV level was made at $E_d = 5.0$ MeV with the proton counter at 50° to the deuteron beam and a 5-in.×6-in. NaI(Tl) gamma-ray detector at right angles to the reaction plane and 5 cm from the target. Otherwise, the procedure was the same as in the study of the 2.62- and 2.72-MeV levels.

The gamma-ray yield from the 3.39-MeV level was quite low, indicating that it decays preferentially by neutron emission. Some evidence was seen for decay to the 2.62-MeV level with a partial width of ~5%; however, this evidence was not conclusive and we set the limit $\Gamma_\gamma/\Gamma < 0.1$ for the gamma decay of the B^{12} 3.39-MeV level. The efficiency for detection of coincidence gamma rays which was used in setting this limit was obtained from the gamma-ray yield of the 2.62-MeV level for which $\Gamma_\gamma/\Gamma = 1$.

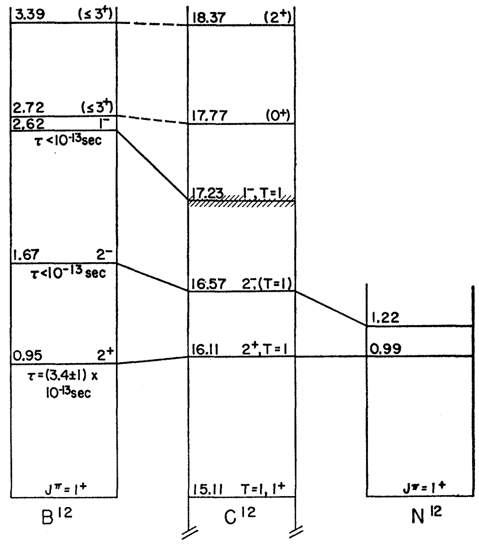

FIG. 14. Partial energy-level diagram for the mass-12 triad. Uncertain spin-parity or isotopic-spin assignments are enclosed in parenthesis. The B^{12} and N^{12} ground states are matched in energy with their isotopic-spin analog at 15.11 MeV in C^{12} in order to exhibit the correspondence of levels belonging to isotopic-spin triads. Levels for which the correspondence seems well-established are connected by solid lines, while levels where the correspondence is less certain are connected by dashed lines. All the information for C^{12} is taken from the latest compilation of Ajzenberg-Selove and Lauritsen (Ref. 6) as are the energy levels for B^{12} and the spin-parity assignments for the B^{12} and N^{12} ground states and the B^{12} 3.39-MeV level. The origin of the remaining information for B^{12} is given in the text. The excitation energies of the N^{12} levels are taken from Ref. 19. *Note added in proof.* An almost identical figure is presented by G. D. Symons and P. B. Treacy, Nucl. Phys. **46**, 93 (1963).

IV. DISCUSSION

An energy-level diagram up to 3.5-MeV excitation in B^{12} is given in Fig. 14. Also shown is the energy level diagram of C^{12} for excitation energies between 15 and 18.38 MeV and the energy level diagram of N^{12} for excitation energies up to 1.5 MeV. The excitation energies of the N^{12} levels are those given by Kavanagh.[19]

An interesting feature of Fig. 14 is that there are just as many states of B^{12} as of C^{12} in the region of excitation energy which is shown. Thus, all the states of C^{12} known in this energy region can have $T=1$ and most probably do. The absence of known $T=0$ states is easily explained as due to the great amount of energy available for α-particle emission (states in C^{12} above 7.37 MeV can decay in this way). Thus, it is quite probable that the $T=0$ levels are too broad to be easily detected.

The order of the s^4p^8 $T=1$ spectrum predicted in

[19] R. W. Kavanagh, Phys. Rev. **133**, B1504 (1964).

intermediate coupling is reported to be $J^\pi=1^+$, 2^+, and 0^+ by Kurath[20] (for $a/K=3-4$) and more recently as $J^\pi=1^+$, 2^+, 0^+, and 2^+ by Amit and Katz.[21] These predictions are in agreement with the 2^+ assignments to the B^{12} 0.95-MeV level and the C^{12} 16.11-MeV level and the most probable assignments of 0^+ and 2^+ to the C^{12} 17.77- and 18.37-MeV levels. They are, therefore, consistent with the most probable assignments to the B^{12} 2.72- and 3.39-MeV levels.

Another noticeable feature of Fig. 14 is the fact that the two odd-parity levels have significantly different energy shifts between B^{12} and C^{12} than the even-parity states. This presumably reflects the dependence of the Coulomb energy, Thomas shift, etc., on the configuration of the analog states. Such dependence has been observed in other isotopic-spin triads. The suggested correspondence of analog states for the B^{12} 2.72- and 3.39-MeV levels implies energy shifts similar to those for the lower even-parity states. Therefore, if the suggested correspondence is correct, the energy shifts are consistent with all four even-parity states belonging to the s^4p^8 configuration.

The spectroscopic factor S of the B^{12} 0.95-MeV level is about five times that of the 2.72-MeV level (see Table II). This can be qualitatively explained if these two levels are the lowest $(J^\pi,T)=(2^+,1)$ and $(0^+,1)$ states of s^4p^8. The B^{11} ground state is predicted[20,21] to be mainly $s^4p_{3/2}{}^7$, while the lowest $(2^+,1)$ state of s^4p^8 is predicted[21] to be mainly $s^4p_{3/2}{}^7p_{1/2}$. Thus the spectroscopic factor for the $B^{11}(d,p)B^{12}$ reaction to this $(2^+,1)$ state should be of order unity. On the other hand, a $(0^+,1)$ state of s^4p^8 cannot contain $s^4p_{3/2}{}^8$ or $s^4p_{3/2}{}^7p_{1/2}$ and thus cannot be connected to $s^4p_{3/2}{}^7$ by the transfer of a single p nucleon.

Talmi and Unna[22] assumed $J^\pi=2^-$ and 1^- for the B^{12} 1.67- and 2.62-MeV levels and used the center of mass of these excitation energies together with the excitation energy of the C^{13}, $J^\pi=\frac{1}{2}^+$, 3.09-MeV level in a comparison which predicted $J^\pi=\frac{1}{2}^+$ for the Be^{11} ground state. Now that the Be^{11} ground state has been conclusively proven[23] to have even parity we can reverse the original argument and state that the center of mass of the excitation energies of the B^{12} 1.67- and 2.62-MeV levels is in excellent agreement with that expected[22] for the two states formed by coupling a $2s_{1/2}$ nucleon to the B^{11} (or C^{11}) ground state.

The lifetime estimate given for the B^{12} 0.95-MeV level in Fig. 14 was obtained by Warburton and Chase[10] using the Doppler-shift attenuation method. These authors also measured Doppler shifts for the B^{12} $1.67\rightarrow 0$ transition (at $E_d=2.1$ MeV) and the $2.62\rightarrow 0.95$ transition (at $E_d=3.0$ MeV). At the time of these measurements the angular distributions of the $B^{11}(d,p)B^{12}$ reaction leading to the 1.67- and 2.62-MeV levels were not known at the appropriate deuteron energies, and so the Doppler-shift measurements were not analyzed quantitatively. The results of Mingay[4] can now be used for that purpose.

From Mingay's angular distribution for the $B^{11}(d,p)B^{12}$ (2.62-MeV level) reaction at $E_d=3.0$ MeV we obtain $\langle\cos\theta_{c.m.}\rangle=0.50\pm0.05$, where $\langle\cos\theta_{c.m.}\rangle$ is the average value of $\cos\theta_{c.m.}$, and $\theta_{c.m.}$ is the angle of the protons to the beam in the center-of-mass system. For the $B^{11}(d,p)B^{12}$ (1.67-MeV level) we need $\langle\cos\theta_{c.m.}\rangle$ for $E_d=2.1$ MeV. This we obtain from the average of the results obtained from the angular measurements measured by Mingay[4] at $E_d=1.8$ and 2.4 MeV. The result is $\langle\cos\theta_{c.m.}\rangle=0.24\pm0.03$. Using these values for $\langle\cos\theta_{c.m.}\rangle$ and the information supplied by Warburton and Chase[10] we obtain (19.0 ± 0.5) keV and (17.5 ± 0.3) keV for the expected Doppler shifts of the $2.62\rightarrow 0.95$ and $1.67\rightarrow 0$ transitions, respectively, for the conditions of the experiment if the lifetimes are very short compared to the stopping times. These results are to be compared to the measured shifts[10] of (19.8 ± 1.1) keV and (16.9 ± 0.6) keV, respectively. It is apparent that the Doppler shifts for both transitions are consistent with lifetimes very short compared to the stopping time of B^{12} nuclei in B^{11} which we take to be[10] $\alpha=(5.1\pm0.6)\times10^{-13}$ sec. Thus, the measurements lead to upper limits on the mean lifetime which we evaluate from the approximation[10] $F'=(\alpha/\tau)/[1+(\alpha/\tau)]$, where $F'(2.62\rightarrow 0.95)=(19.8\pm1.1)/(19.0\pm0.5)$ and $F'(1.67\rightarrow 0)=(16.9\pm0.6)/(17.5\pm0.3)$. For both transitions we have $F'>0.85$ to about three standard deviations, which gives $\tau<10^{-13}$ sec. This is the limit we adopt for both the 1.67- and 2.62-MeV levels.

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