ar Reactions Induced by Heavy Ions (see Ref. 10), p. 72; H. T. Fortune, A. Richter, R. H. Siemssen and J. W. Tippie, *ibid.*, p. 69; R. H. Siemssen, H. T. Fortune, R. Malmin, A. Richter, J. W. Tippie, and P. P. Singh, Phys. Rev. Letters 25, 536 (1970); G. C. Morrison, H. T. Fortune and R. H. Siemssen, Phys. Rev. C 3, 2133 (1971).

[12]R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C 1, 795 (1970).

[13]J. Orloff and W. W. Daehnick, Phys. Rev. C 3, 430 (1971).

[14]E. H. Auerbach and C. E. Porter, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei, Asilomar, Pacific Grove, California, 1963*, edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (Univ. of California Press, Berkeley, 1963), p. 19.

[15]L. McFadden and G. R. Satchler, Nucl. Phys. 84, 177 (1966).

[16]M. W. Kermode, Nucl. Phys. A104, 49 (1967), and references contained therein; S. Ali and A. R. Bodner, Nucl. Phys. 80, 99 (1966).

[17]J. V. Maher, R. H. Siemssen, M. W. Sachs, A. Weidinger, and D. A. Bromley, in *Proceedings of the International Conference on Reactions Between Complex Nuclei, Heidelberg, 1969*, edited by R. Bock and W. R. Heinz (North-Holland, Amsterdam, 1970), p. 60.

[18]R. W. Barnard and G. D. Jones, Nucl. Phys. A111, 17 (1968).

[19]L. Broman and D. J. Pullen, Nucl. Phys. A110, 161 (1968).

[20]J. R. Priest and J. S. Vincent, Phys. Rev. 182, 1121 (1969).

[21]R. H. Siemssen, M. L. Halbert, M. Saltmarsh, and A. van der Woude, Phys. Rev. C 4, 1004 (1971); R. H. Siemssen, C. L. Fink, L. R. Greenwood, and H. J. Korner, Phys. Rev. Letters 28, 626 (1972); G. J. Wozniak, H. L. Harney, K. H. Wilcox, and J. Cerny, Phys. Rev. Letters 28, 1278 (1972); C. Chasman, S. Cochavi, M. J. LeVine, and A. J. Schwarzschild, Phys. Rev. Letters 28, 843 (1972).

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^{13}C States via the ^{12}C(d, p)^{13}C Reaction*

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Protons from the ^{12}C(d, p)^{13}C reaction were analyzed with a magnetic spectrograph. Bombarding energies ranged from 14.0 to 15.5 MeV and observation angles ranged from 20 to 120°. Eight states were found in ^{13}C between 10.7- and 12.2-MeV excitation energy. Excitation energies and (widths) in keV are: 10 755 ± 5 (56 ± 2), 10 818 ± 5 (24 ± 3), 10 997 ± 8 (82 ± 15), 11 080 ± 5 (<8), 11 748 ± 10 (107 ± 14), 11 851 ± 5 (68 ± 4), 11 970 ± 40 (~260), and 12 108 ± 5 (81 ± 8). The level at 11 851 has not been reported before. Uncertainties in excitation energies are reduced by as much as a factor of 4 from previous work.

I. INTRODUCTION

The purpose of the present work is to provide accurate positions and widths for states in ^{13}C in the 10.5- to 12.2-MeV region of excitation. Although many reactions have been used previously to investigate this region, a glance at a compilation of nuclear data[1] shows that in most cases, excitation energies are not known to better than 20 keV and the widths are quite uncertain and are in many cases only estimates. States above 10.651 MeV are unbound to α as well as neutron emission and a major difficulty with any investigation of the region is that levels overlap and all but one have widths between 20 and 300 keV. Spectra from reactions that leave ^{13}C as the residual nucleus are usually complicated by the presence of contaminant groups which either obscure the broad levels or make analysis of the data difficult. Although contaminants are not usually a serious problem in reactions which have ^{13}C as the compound nucleus, the determination from resonance data of accurate widths and positions in a complicated energy spectrum can be difficult. In the present work the ^{12}C(d, p)^{13}C reaction was chosen since targets can be made with few contaminants, thus allowing relatively "clean" proton spectra to be obtained. Because of the complicated energy spectrum, we determined positions and widths of the levels by fitting the proton spectra with an incoherent sum of simple Breit-Wigner resonances plus a quadratic background term. The results of this analysis are discussed and presented below.

II. EXPERIMENTAL

Self-supporting natural carbon targets were made from 20- and 40-μg/cm^2 commercial carbon foils. Deuteron beams were produced with the University of Notre Dame FN tandem Van de

Graaff accelerator with the nominal energy of the incident deuteron beam being determined by magnetic analysis. The reaction products were momentum analyzed with the 50-cm broad-range magnetic spectrograph and nuclear track plates mounted at the focal surface of the spectrograph were employed as particle detectors. Runs were made at laboratory angles ranging from 20 to 120° and at the nominal beam energies of 14.0, 14.5, 15.0, and 15.5 MeV. The data taken at forward angles such as 20 and 30° are not presented, since the groups above 10.75-MeV excitation did not appear sufficiently above background to allow analysis. A comparison of the yields to the 10.818- and 10.755-MeV levels at 60, 90, and 120° (Figs. 1 and 2) suggests this decrease in yield at forward angles to states above 10.75 MeV. Data taken at 15.5 MeV are also not presented because of low yields to the states of interest.

Because the range of the 50-cm spectrograph did not allow the simultaneous measurement of the ground state and the states of interest, separation energies were measured with respect to a narrow level at 9.5 MeV. The excitation energy of this level is given as 9.499 ± 0.004 MeV in the latest compilation of Ajzenberg-Selove,[1] with a reported width of less than 5 keV. This excitation energy appears to come primarily from the ^{12}C-$(n, n)^{12}$C resonance work of Davis and Noda.[2] Since this value is lower than the previously reported values of 9.509 ± 0.008[3] and 9.51 MeV,[4] we used the ^{11}B(^{3}He, p)^{13}C reaction to make an independent measurement of the excitation energy. The value of 9.502 ± 0.006 MeV obtained from an average of two runs is in good agreement with the compilation value. We used the compilation value together with the measured energy of the proton group leading to this state to calculate an

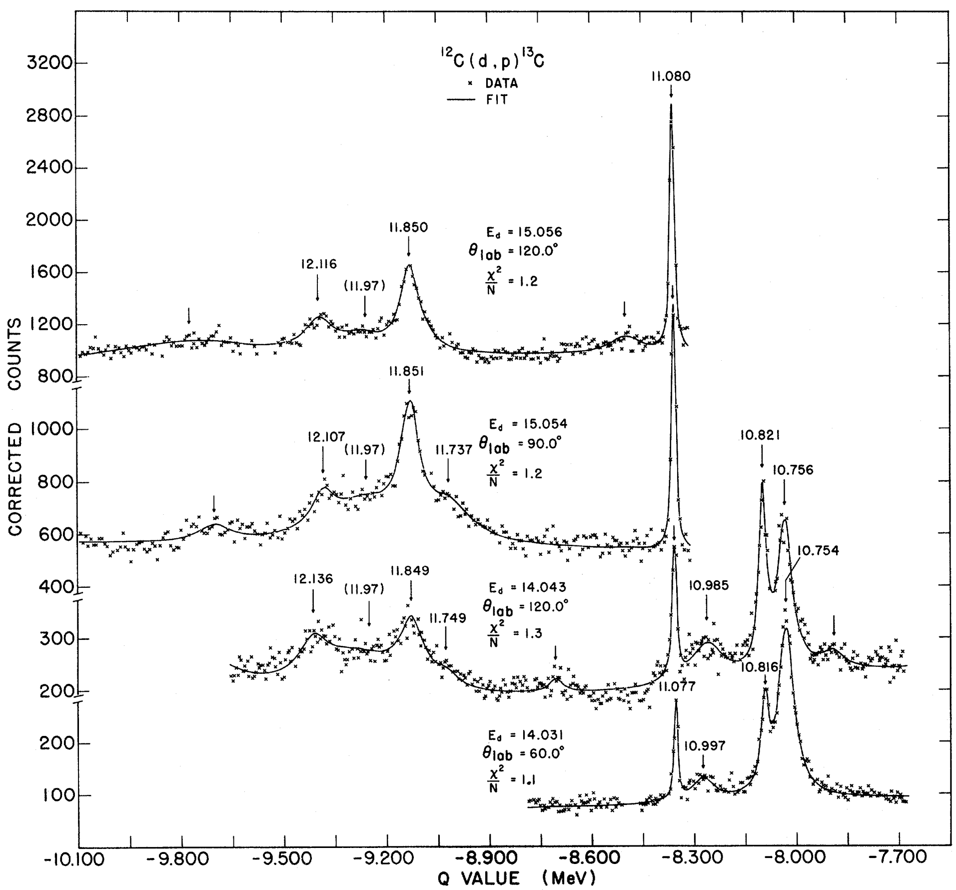

FIG. 1. Proton spectra from the ^{12}C$(d, p)^{13}$C reaction. The curves are fits and the numbers on the arrows give the excitation energies obtained. The number (11.97) indicates the location of a group at this excitation energy. The bombarding energies derived from the position of the 9.499-MeV group (not shown) or the 11.080-MeV group are given for each spectrum as are the observation angles and values of χ^2/N. The number of proton tracks per strip were corrected for the variation in solid angle with position on the plate and converted to an interval in Q value and the position was converted to Q value for this reaction.

input energy for the three (d, p) runs which included this state. The input energies for the other runs were calculated using our excitation energy for the narrow state at 11.080 MeV. The separation energies measured from the 9.499-MeV state or the 11.080-MeV state are quite insensitive to the input energy, and the resulting excitation energies depend mainly on the measured energy differences of the proton groups and the excitation energy assumed for the reference state.

III. ANALYSIS

Spectra from the $^{12}C(d, p)^{13}C$ reaction at the laboratory angles of 60, 90, 100, and 120° are shown in Figs. 1 and 2 where several broad groups are evident in the 11.5- to 12.5-MeV region of excitation. In order to extract accurate values of the positions and widths of these levels, each spectrum was fitted as an incoherent sum of simple Breit-Wigner resonances plus a quadratic background term. A search program written at this laboratory (by G. L. Marolt and J. D. Goss) minimized χ^2 by varying the amplitude, position, and width of each level as well as the background parameters. In some spectra this means that up to 36 parameters were searched on simultaneously. The results of the fitting are shown in Figs. 1 and 2. The solid lines are the computer-generated fits to the data, and the excitation energies obtained are given above each level. Arrows with no excitation energies listed indicate the location of groups which were necessary to adequately fit the data. Since these groups appear only a few times, and because they would correspond to high excitation energies, it has not been possible to identify the residual nucleus. The ^{13}C levels were identified kinematically by variations with energy and angle. Because some groups are more in-

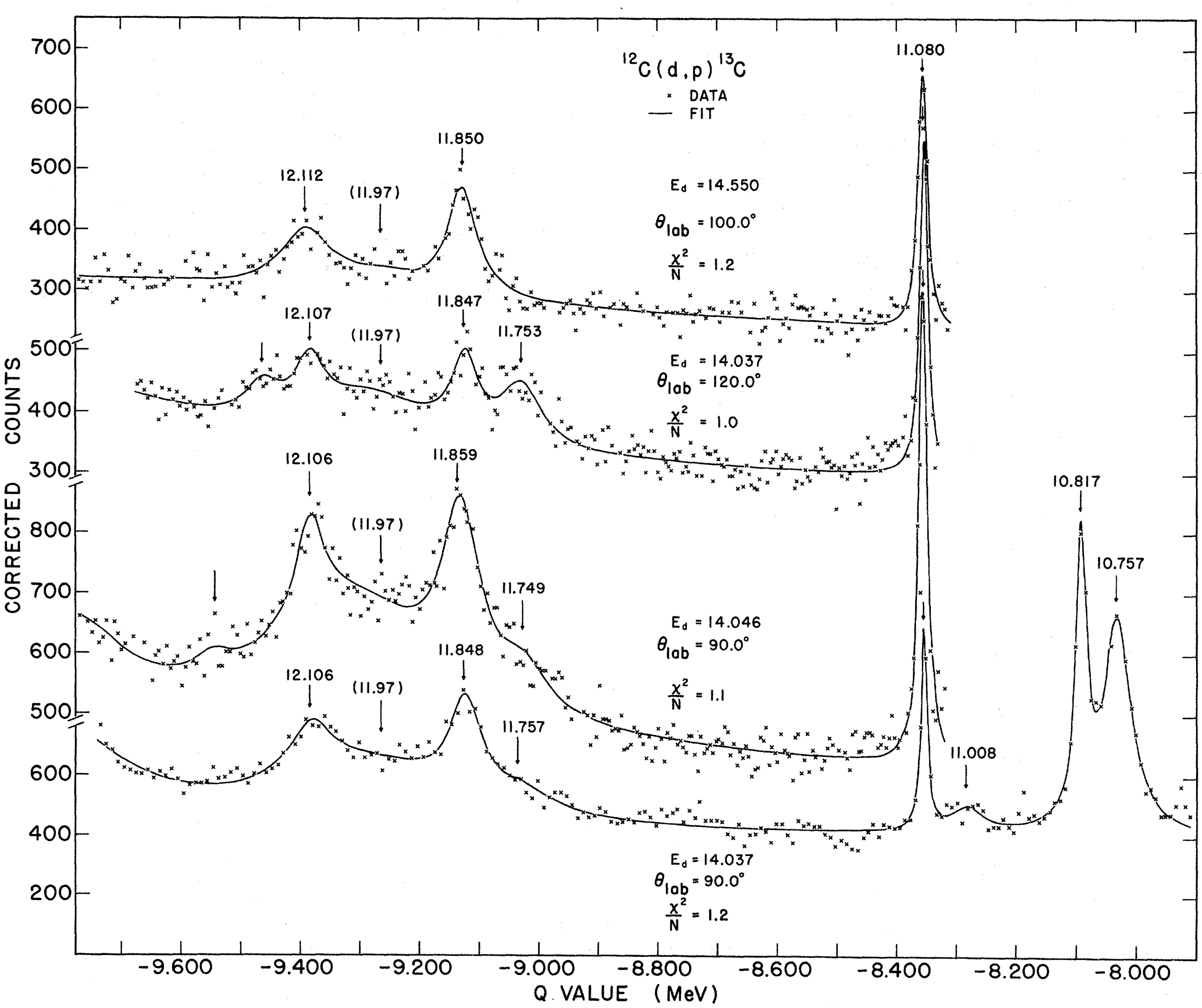

FIG. 2. Proton spectra from the $^{12}C(d, p)^{13}C$ reaction. See caption of Fig. 1 for meanings of labels.

tense in one spectrum than in another, the excitation energy and width of each level was obtained by a weighted average, the weighting factor being determined from the peak-to-background ratio. Widths have been corrected for target thickness and kinematic broadening ($\Delta\theta^* dQ/d\theta$). In all cases except for the narrow levels at 10.82 and 11.08 MeV, these corrections are less than 1%. For the state at 10.82 MeV the corrections are about 5% and only an estimate of the width is possible for the level at 11.08 MeV. The uncertainty in the width quoted is the standard deviation of the mean. The uncertainty in the excitation energy is twice the standard deviation of the mean combined quadratically with the uncertainty in the reference state (4 keV).

IV. RESULTS AND DISCUSSION

A. 10.755- and 10.818-MeV Levels

The latest tabulation of Ajzenberg-Selove[1] indicates that the two levels near 10.8-MeV excitation have been seen with a variety of reactions but in only a few cases have both levels been observed at the same time. In a recent measurement of the $^{11}B(^3He, p)^{13}C$ reaction, Meynadier, Chanut, and Drain[5] found levels at 10.76 ± 0.01 MeV and 10.82 ± 0.01 MeV but no level widths were reported. Silbert,[6] in an investigation of the $^{14}N(t, \alpha)^{13}C$ reaction, observed a level at 10.809 ± 0.020 MeV with a poorly resolved group on its high-energy side at 10.736 ± 0.020 MeV. The widths of the two levels were estimated to be less than 30 keV. Fossan *et al.*[7] from their ^{12}C neutron total cross-section measurements reported a level at 10.74 MeV with a width of 65 keV, and the possibility of a second level at 10.9 MeV. In the present work both states were strongly populated. Excitation energies of 10.755 ± 0.005 MeV and 10.818 ± 0.005 MeV were obtained and the widths were measured to be 56 ± 2 and 24 ± 3 keV, respectively.

B. 10.997-MeV Level

A rather weak proton group is evident in the present experiment near 11 MeV excitation. The level was determined to be at an excitation of 10.997 ± 0.008 MeV with a width of 82 ± 15 keV. The width is considerably larger than the 37 keV given in the compilation[1] for a level at 11.000 ± 0.020 MeV. From resonance studies of $^9Be(\alpha, n)$-^{12}C, Davids[8] and James, Jones, and Wilkinson[9] have both observed a level at 11.01 MeV with a width of approximately 55 keV. Silbert,[6] in a study of the $^{14}N(t, \alpha)^{13}C$ reaction, reported a level at 11.000 ± 0.020 MeV having a width of approximately 30 keV. Hall and Bonner[10] have also observed a level at 11.01 MeV with a width less than 80 keV from their investigation of the $^{12}C(n, n'\gamma_{4.43})^{12}C$ reaction. In most cases the reported width is less than that measured in the present experiment. Since there are no uncertainties quoted for these widths, it is not clear whether or not a discrepancy exists.

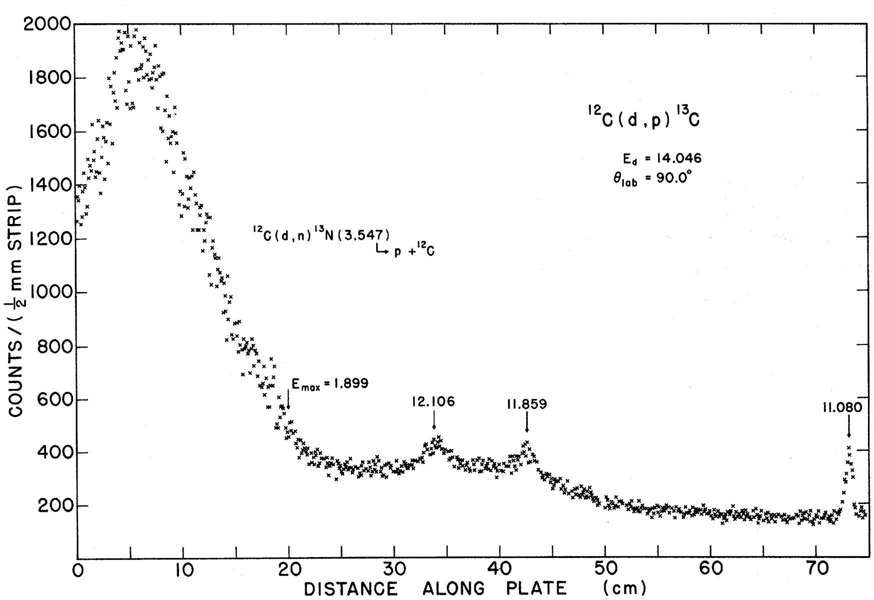

FIG. 3. Proton spectrum from deuteron bombardment of carbon target showing how the group from $^{12}C(d,n)^{13}N(3.547) \rightarrow {}^{12}C + p$ obscures the region above 12.2 MeV excitation.

TABLE I. Comparison of excitation energies and widths of levels in ^{13}C measured in this work with values given in a recent compilation (see Ref. 1).

Compilation excitation energy [a] (MeV ± keV)	Width (c.m.) (keV)	Number of runs	This work Excitation energy [b] (MeV ± keV)	Width (c.m.) (keV)
10.753 ± 5	≈50	3	10.755 ± 5	56 ± 2
10.809 ± 20	<30	3	10.818 ± 5	24 ± 3
11.000 ± 20	37	3	10.997 ± 8	82 ± 15
11.078 ± 20	<4	3	11.080 ± 5	<8
11.721 ± 30	125 ± 20	5	11.748 ± 10	107 ± 14
		7	11.851 ± 5	68 ± 4
11.97	≈150	5	(11.97 ± 40) [c]	≈260
12.104 ± 8	125 ± 30	6	12.108 ± 5	81 ± 8

[a] Excitation energies given with respect to the $^{9}Be + \alpha$ threshold at 10.651 MeV.
[b] Excitation energies measured with respect to the 9.499 ± 0.004-MeV state.
[c] The possibility that more than one level exists in this region is discussed.

C. 11.080-MeV Level

An intense-narrow proton group corresponding to an excitation of 11.080 ± 0.005 MeV appears in the present experiment. The experimental resolution allows us to set an upper limit of 8 keV for the width of the level. The excitation energy and width both agree well with the compilation[1] which lists a level at 11.078 ± 0.020 MeV with a width less than 4 keV.

D. 11.748-, 11.851-, and 11.97-MeV Levels

Levels are reported in the compilation[1] at 11.721 ± 0.030 and 11.97 MeV with widths of 125 ± 30 keV and approximately 150 keV, respectively. We observed three proton groups in this region of excitation. A rather weak group corresponds to an excitation of 11.748 ± 0.010 MeV with a width of 107 ± 14 keV, and a strong group corresponds to a previously unreported level at an excitation of 11.851 ± 0.005 keV with a width of 68 ± 4 keV. To fit the data in the excitation region above the 11.851-MeV state, it was necessary to include a broad group although no well-defined group stands out from the background. The results of the fitting shown in Figs. 1 and 2 show a level near 11.97 MeV with a width of approximately 260 keV. The group is not sufficiently resolved to allow determination of the excitation to closer than 40 keV, the fits being insensitive to the location of the group and the width is considerably larger than the 150 keV reported previously. The group may in fact be more than one level, but the present data are not sufficient for such a determination.

E. 12.108-MeV Level

The present experiment shows a prominent group on the low-energy side of the broad structure at 11.97 MeV and an excitation energy of 12.108 ± 0.005 MeV and a width of 81 ± 8 keV were measured. The excitation energy agrees well with that in the compilation[1] which lists a level at 12.104 ± 0.008 with a width of 125 ± 30 keV.

V. SUMMARY

The results of the present experiment are listed in Table I as are those from the compilation of Ajzenberg-Selove.[1] In most cases the agreement is excellent. A possible discrepancy in the width of the 11.0-MeV level was pointed out above. It was also noted that the level at 11.851 MeV with a width of 68 keV was not reported previously. A broad structure near 11.97 MeV was observed, but the width is considerably larger than the previously reported value.

A study of the states above 12 MeV excitation with the present reaction was hampered by the presence of an intense proton group from the competing reaction, $^{12}C(d,n)^{13}N^{*}(p)$. A spectrum of this group is shown in Fig. 3. Background from the group made analysis of higher states very uncertain, and the results of these measurements are not presented.

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[1]F. Ajzenberg-Selove, Nucl. Phys. A152, 1 (1970).
[2]J. C. Davis and F. T. Noda, Nucl. Phys. A134, 361 (1969).
[3]F. Ajzenberg-Selove and T. Lauritsen, *Landolt-Bornstein: Numerical Data and Functional Relationships in Science and Technology*, edited by K.-H. Hellwege (Springer-Verlag, Berlin, 1961), New Series, Vol. 1.
[4]T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear*

Data Sheets, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences – National Research Council, Washington, D. C., 1962).
[5]C. Meynadier, Y. Chanut, and D. Drain, Nuovo Cimento Letters 4, 1063 (1970).
[6]M. G. Silbert, Phys. Rev. 127, 2113 (1962).
[7]D. B. Fossan, R. L. Walter, W. E. Wilson, and H. H. Barschall, Phys. Rev. 123, 209 (1961).
[8]C. N. Davids, Nucl. Phys. A110, 619 (1968).
[9]D. B. James, G. A. Jones, and D. H. Wilkinson, Phil. Mag. 1, 949 (1956).
[10]H. E. Hall and T. W. Bonner, Nucl. Phys. 14, 295 (1959).

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Calculations of Allowed Beta Decay in the $(0d, 1s)$ Shell*

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Allowed β-decay transition rates and half-lives have been calculated for $(0d, 1s)$ shell nuclei with $A = 17$–22, 23–24, 27–29, 30–34, and 35–39. For nuclei with $A = 17$–22 and 34–39, the calculated logft values have a rms deviation of 5% from experiment, with no discrepancies greater than 12%. For nuclei nearer the middle of the shell there are more significant discrepancies between experiment and theory. The calculated logft values are used to predict the half-lives of some light elements. The predicted half-lives for which there are no experimental measurements are: ^{20}Mg (0.1 sec), ^{21}O (1.2 sec), and ^{22}O (0.15 sec). The logft values relevant to the solar neutrino experiment are discussed.

I. INTRODUCTION

This paper presents calculations of strengths of allowed β-decay transitions for the $(0d, 1s)$ shell nuclei with $A = 17$–22, 23–24, 27–29, 30–34, and 35–39. The shell-model wave functions of Wildenthal *et al.*[1–6] are used to describe the initial and final nuclear states. We present calculated logft values for the approximately 100 transitions for which there are experimental measurements, and we give predictions for approximately an equal number of decays which may be measurable. We also use these calculated logft values to predict β-decay half-lives. As will be seen, the agreement between the present calculations and experiments is consistently quite good for the nuclei for which the complete $(0d, 1s)$ shell-model basis space could be used. On the other hand, agreement with experiment is not as consistently good for calculations in the middle of the shell where significant truncations of the model space were necessary.

The calculation of β-decay transition rates is interesting for several reasons. (1) There are few uncertainties in the operators involved and in the connection between the experimentally measured quantities and those predicted by the theory. (2) Because the β-decay operators only connect single-particle states which have the same orbital angular momentum and because the initial and final states are in different nuclei, the matrix elements of the β-decay operators tend to be sensitive to aspects of wave functions not extensively tested in comparisons of theoretical results with nucleon transfer and γ-decay data. Hence, we have the opportunity to learn more about the detailed efficacy of the extant sets of wave functions in the $(0d, 1s)$ shell. (3) As indicated above, there are a large number of experimentally measured decays which can be compared with calculated values. (4) If the calculations turn out to be reasonably successful, the results can be used to predict the half-lives of some of the neutron- and proton-rich nuclei which have not yet been observed. Such predictions might aid in designing experiments to observe these nuclei. And (5) calculated β-decay transition rates are needed to evaluate the results of Davis's experiment[7] to measure the solar neutrino flux using the $^{37}\mathrm{Cl} + \nu \rightarrow {}^{37}\mathrm{Ar} + e$ reaction.

II. DESCRIPTION OF THE CALCULATION

A. Operators

β-decay transition rates are expressed in terms of a logft, where t is the partial half-life for the decay to a given final state and f is a "statistical rate function" which takes account of the energy released in the decay and the Coulomb field of the final nucleus.[8] For allowed decays, ft is given