Isotopic-Spin Selection Rule Violation in the $B^{10}(d,\alpha)Be^8$ Reaction*

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All previous tests of the isotopic-spin selection rule in (d,α) reactions were obscured by statistical weight factors because in each case the initial and final nuclear states had spin and parity 0^+. The $B^{10}(d,\alpha)Be^8$ reaction provides a test of the isotopic-spin selection rule free from this restriction. The energy levels of Be^8 near the lowest $T=1$ level were studied with the $Li^6(He^3,p)Be^8$ and $Be^9(He^3,\alpha)Be^8$ reactions as well as with the $B^{10}(d,\alpha)Be^8$ reaction. Energy levels in Be^8 were found at 16.623 ± 0.010 Mev, 16.921 ± 0.010 Mev, and 17.637 ± 0.006 Mev. The widths are 95 ± 20 kev, 85 ± 20 kev, and <15 kev, respectively. The first of these levels is the lowest $T=1$ state, whereas the second is $T=0$ and the third probably $T=1$. Energy levels at 16.08 Mev and a $J=2$ level at 17.7 Mev, reported by other laboratories, were not observed. The ratio of the differential cross sections for formation of the 16.62- and 16.92-Mev levels was measured over a range of angles and bombarding energies. The ratio is about 1.4 and is roughly constant for both the $Li^6(He^3,p)Be^8$ and $B^{10}(d,\alpha)Be^8$ reactions. This implies complete violation of the selection rule because the latter reaction should not go to the $T=1$ level. Arguments are given which indicate that the $T=0$ impurities in the 16.62-Mev $T=1$ level are probably quite small. Consequently, the failure of the selection rule probably results from the complete intermixing of $T=0$ and $T=1$ states in the C^{12} compound nucleus near 28-Mev excitation. Groups from the $C^{12}(He^3,p)N^{14}$ reaction were seen corresponding to levels in N^{14} at 5.691 ± 0.008, 5.834 ± 0.008, 6.203 ± 0.008, and 6.440 ± 0.008 Mev.

INTRODUCTION

THE assumption of the charge independence of nuclear forces leads[1] to isotopic-spin selection rules in nuclear reactions. Violations of these selection rules have been observed[2–5] in a number of (d,α) reactions with the intensity of the forbidden group varying from 5% to 10% of the intensity of an adjacent, allowed group. Recently, Hashimoto and Alford[5] pointed out that, in all these (d,α) reactions, the violation is more severe than the simple forbidden-to-allowed intensity ratio indicates. They noticed that all of these forbidden transitions proceed from a $J^\pi=0^+$ target nucleus to a $J^\pi=0^+$ $(T=1)$ level in the residual nucleus. Therefore, statistical weight factors based on angular momentum and parity alone may reduce the transition rate by a factor of 5 or 6. The isotopic-spin selection rule thus appears to reduce the intensity of the forbidden group by only a factor of 2 or 3. This is a rather serious breakdown of the selection rule.

Direct observation of such a large violation would be interesting, since other experiments (for example, the photodisintegration of C^{12}) do not suggest such large isotopic-spin impurities in the compound nucleus. The present work was performed to study an isotopic-spin selection rule violation in a (d,α) reaction which was not obscured by statistical weight factors on angular momentum and parity. The $B^{10}(d,\alpha)Be^8$ reaction was chosen, since the ground state of B^{10} is 3^+, and the lowest $T=1$ level in Be^8 is 2^+, unlike the usual 0^+ to 0^+ case.

Knowledge of the level structure of Be^8 was needed to identify the lowest $T=1$ level and nearby $T=0$ levels that might be observed with the $B^{10}(d,\alpha)Be^8$ reaction. Slattery, Chapman, and Bonner[6] studied the $Li^7(d,n)Be^8$ reaction. They reported levels in this region at 16.07 and 16.67 Mev with widths of 310 and 190 kev, respectively. A group of neutrons that would correspond to a level at about 16.9 Mev was ascribed to an oxygen contaminant in the target. Levels at 17.60 and 18.19 Mev were also seen. After the present data had been taken and a preliminary report given,[7] Dietrich and Cranberg[8] used time-of-flight techniques to study the $Li^7(d,n)Be^8$ reaction. They report levels at 16.64, 16.9, 17.64, and 18.15 Mev. Goward and Wilkins[9] have studied alpha-particle emission from C^{12} following $E1$ gamma-ray absorption. They found a prominent group corresponding to a level in Be^8 at 16.9 Mev and two smaller groups on either side. The latter suggested energy levels at 16.5 and 17.7 Mev. The 16.5-Mev level was assigned a spin $J=0$ or 2 and isotopic spin $T=0$ or 1. The 16.9-Mev level was assigned $J=2$ and $T=1$. The level at 17.7 Mev was assigned $T=1$ and was regarded as distinct from the well known $J=1$ level at 17.64 Mev.

Since there is some disagreement among the results of previous investigations of Be^8 level structure, the $Li^6(He^3,p)Be^8$ and $Be^9(He^3,\alpha)Be^8$ reactions were used in the present work to observe the levels. In these reactions the isotopic-spin selection rule should have no effect on the relative intensities of $T=0$ and $T=1$ levels.

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EXPERIMENTAL PROCEDURE

The nuclear reaction data were taken with the Notre Dame broad-range magnetic spectrograph used in conjunction with the 4-Mev electrostatic accelerator. This experimental apparatus has been described elsewhere.[10]

All the targets were made by evaporating the elemental material onto thin Formvar films. The most successful boron evaporations were made using a carbon boat. The boron targets had a stopping of about 15 kev for the alpha particles which lead to the $T=1$ level in the $B^{10}(d,\alpha)Be^8$ reaction. The Formvar backings of these targets were about 4 kev thick to 4-Mev deuterons. The lithium targets consisted of a lithium layer, about 25 kev thick to 3.5-Mev He^3 ions, evaporated from a tantalum boat onto a very thin, single film of Formvar. The Formvar film was as thin as could be picked up from the water surface with a $\frac{5}{16}$- by $\frac{7}{16}$-in. target frame. Only these very thin backings were able to withstand the He^3 beam and even with them it was necessary to spread the beam out over a wider area of the target. The beryllium targets were made in the same way as the lithium targets and were of about the same thickness, but Formvar backings of normal thickness could be used.

The assignment of observed particle groups to a given reaction was based on the constancy of the calculated Q value for various bombarding energies and observation angles.

Eight exposures were taken with the $B^{10}(d,\alpha)Be^8$ reaction, covering the range of excitation energies in Be^8 from 15.5 to 19.0 Mev. The bombarding energies ranged from 3.80 to 4.25 Mev and the observation angle from 35° to 110°. Lower bombarding energies and larger observation angles could not be used, because the resulting alpha-particle tracks in the nuclear emulsion were too short for convenient counting. The minimum observation angle was 35° because at smaller angles deuterons scattered from the hydrogen in the target struck the plate in the same region as the alpha particles. These scattered deuterons produced large numbers of tracks on the emulsion which were so similar in length to the alpha-particle tracks that they could not be distinguished.

Seven successful exposures were made with the $Li^6(He^3,p)Be^8$ reaction. These covered the region of excitation in Be^8 from 14.5 to 18.0 Mev. The bombarding energies ranged from 3.50 to 4.25 Mev and the observation angle from 20° to 120°.

Two exposures were taken with the $Be^9(He^3,\alpha)Be^8$ reaction at observation angles of 15° to 70° and a bombarding energy of 3.75 Mev. Excitation energies from 16.5 to 18.0 Mev were covered by the exposures.

A search was made with the $Li^7(d,p)Li^8$ reaction for an energy level in Li^8 between the ground state and the known level at 0.975 Mev. If such a level did exist there would be an analogous $T=1$ level in Be^8. Knowledge of the isotopic spins of the Be^8 levels is required to interpret results from the $B^{10}(d,\alpha)Be^8$ reaction. Three exposures of 700, 500, and 1000 μcoul were made at 35°, 70°, and 110° observation angle, respectively, with 3.5-Mev bombarding energy.

Absolute differential cross sections of the $B^{10}(d,\alpha)Be^8$ and $Li^6(He^3,p)Be^8$ reactions leading to the lowest $T=1$ and a nearby $T=0$ level in Be^8 were measured by comparing the intensity of the group in question with the intensity of groups from the $B^{10}(d,p)B^{11}$ or $Li^6(He^3,p)Be^8$ reactions. The absolute differential cross sections for the latter reactions have been measured.[11,12] In many cases, groups from other reactions were superimposed on the wide groups from the Be^8 levels. The total number of tracks in a group was then calculated by the following method. Exposures in which the group was not obscured were used to find the level width. The observed distribution of tracks on the plate could be fitted with a Breit-Wigner single-level formula and the width, Γ, determined. This formula was integrated to give the total number of tracks, N, in terms of Γ and σ_r, where σ_r is the number of tracks per counting strip at the maximum. The result was $N=\pi\sigma_r\Gamma/2$. For groups that were partially obscured σ_r was found by fitting the unobscured portion, Γ was calculated in units of number of counting strips, for the appropriate position on the plate, and N then found from the above expression.

The bombarding energies used in the Q-value calculations were obtained from the trajectory radius and magnetic field in the beam analyzer. This method was checked by the more accurate procedure of determining the bombarding energy from the measured energy of particles which had been elastically scattered out of the incident beam. The latter method was not used for all exposures since it is less convenient and since larger uncertainties in the Q-value measurements were produced by other factors.

The output energies of the particle groups corresponding to the wide Be^8 levels were obtained in the following way. First, the position on the nuclear track plate of the center of the observed group was obtained. Then a correction was added so that the energy calibration which had been made with narrow peaks from a polonium source could be used with these wide groups. This correction shifted the reference point from the center of the group to the $\frac{1}{3}$-height point of the high-energy edge of a narrow group at the given position. Next, a second correction was added to compensate for the shift in the particle group produced by the use of a beam spot which measured $1\frac{1}{2}$ mm in the energy-sensitive direction, rather than the $\frac{1}{2}$ mm of the polonium

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source used for calibration. Next, the energy corresponding to this corrected position was obtained from the spectrograph calibration. Finally, a correction for the target thickness was made by adding one half of the target stopping.

The effect of the target thickness on the width of the groups was removed by assuming that the natural level width and the target thickness combined quadratically. This approximation introduced smaller uncertainties than those already present from other effects.

The thickness of the targets was determined by studying the widths and positions of groups of particles from various reactions and from elastic scattering.

All Q values reported in this work are based on a polonium alpha-particle energy of 5.3056 Mev. This is the calibration standard suggested at the recent McMaster Conference on Nuclidic Masses.[13]

EXPERIMENTAL RESULTS

$B^{10}(d,\alpha)Be^8$ Reaction

Figure 1 shows portions of the plots for three $B^{10}(d,\alpha)Be^8$ exposures which show groups corresponding to Be^8 levels at 16.92- and 16.62-Mev excitation. One of these levels is the lowest $T=1$ level and should be forbidden in this reaction. These three plots are for runs taken at 4.0-Mev bombarding energy and at angles of 35°, 50°, and 70°, respectively.

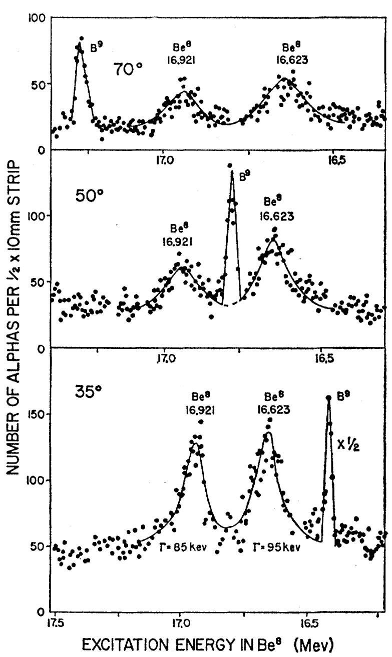

FIG. 1. Portions of the plots of three $B^{10}(d,\alpha)Be^8$ exposures showing groups corresponding to the 16.623- and 16.921-Mev levels in Be^8. A triton group from the $B^{10}(d,t)B^9$ reaction also appears. The usual abscissa scale of distance along the plate has been converted to excitation energy in Be^8 to compare the three plots. This scale, of course, does not apply to the triton group. The bombarding energy was 4.0 Mev. The 16.623-Mev level is the lowest $T=1$ level in Be^8, and its formation in this reaction should be forbidden.

All of the exposures showed a continuous background of alpha particles from the three-body breakup of the C^{12} compound nucleus. A group from the $B^{10}(d,t)B^9$ reaction is seen on the plots. The triton tracks were indistinguishable from the alpha tracks, and the identification of the group was based on its motion with change of observation angle. On several exposures groups were seen which probably arose from the 17.64- and 18.15-Mev levels of Be^8. The intensity of these groups relative to background was, however, low, and as the present report is primarily concerned with the lowest $T=1$ state, the analysis of the groups leading to higher levels will be reported later along with additional work that is in progress. No level in Be^8 at 16.08 Mev was observed. The large alpha-particle background present in this reaction could, however, obscure a group leading to such a level, particularly if the level was wide.

The data used to obtain Q values and widths for the two wide Be^8 levels are listed in Table I. The constancy of the Q values for different bombarding energies and observation angles shows that the alpha-particle groups are properly identified with this reaction. If a ground-state Q value of 17.819 Mev is assumed,[14] the average Q values listed give excitation energies of 16.623 ± 0.010 Mev and 16.919 ± 0.010 Mev.

The weighted average is listed for the width of each level. In forming this average greater weight was given to the measurements with the small widths, since target thickness effects and poor statistics tend to increase the observed width of a level.

$Li^6(He^3,p)Be^8$ Reaction

Figure 2 shows a plot of the exposure for the $Li^6(He^3,p)Be^8$ reaction made at 3.5-Mev bombarding energy and 40° observation angle. It covers Be^8 excitation from 15.75 to 17.80 Mev. Three Be^8 levels are visible: the narrow level at 17.64 Mev and the two wide levels at 16.92 and 16.62 Mev. All the other groups on the plate correspond to energy levels in N^{14} and F^{18} and come from reactions on the carbon and oxygen in the target. The rising background of protons on the left side of the figure is produced by the three-body breakup of the B^9 compound nucleus into two protons and a Li^7 nucleus. This reaction has a threshold corresponding to an excitation in Be^8 of 17.25 Mev. A background from the $Li^6(He^3,p)2He^4$ reaction underlies the whole plot.

All the exposures were carefully examined for groups corresponding to energy levels in Be^8 at 16.08 Mev

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TABLE I. Q values and level widths for the 16.62-Mev and 16.92-Mev levels from the $B^{10}(d,\alpha)Be^8$ reaction.

Observation angle (deg)	Bombarding energy (Mev)	16.62-Mev level Q (Mev)	16.62-Mev level Γ (kev)	16.92-Mev level Q (Mev)	16.92-Mev level Γ (kev)
35	4.005	1.194±0.020	81±20	0.902±0.020	66±20
50	4.005	1.195±0.020	113±30	0.881±0.020	110±30
70	4.005	1.203±0.020	122±30	0.897±0.020	98±30
35	4.205	1.191±0.020	130±30	0.904±0.020	118±30
35	3.865	1.198±0.020	81±20	0.907±0.020	81±20
50	3.865	1.196±0.020	121±30	0.910±0.020	82±20
Weighted mean		1.196±0.010	95±20	0.900±0.010	85±20

and another level near the known 17.64-Mev level. The 16.08-Mev level would have been observed if its intensity were more than one-tenth the intensity of the 16.62-Mev level and if it had the same width. For a narrower level the limit would be correspondingly lower. A group leading to another level near the known 17.64-Mev level may have been obscured by the rising background caused by the $Li^6(He^3,2p)Li^7$ three-particle reaction. Such a level, however, would have been seen if it were one-fifth the intensity of the 17.64-Mev Be^8 level and if it had the same width.

The positions and widths of the Be^8 levels observed with the $Li^6(He^3,p)Be^8$ reaction are given in Table II. The gaps in this table represent the obscuring of Be^8 levels by groups from reactions with the carbon and oxygen in the target. The width of the 17.64-Mev level is less than the energy spread of the particle groups caused by instrumental and target effects, and hence could not be measured. The rather large uncertainty in Q value for this narrow level arises from uncertainty of the target stopping and the fact that the target was in the transmission position for the runs showing this group. If a ground-state Q value of 16.786 Mev is assumed,[14] the average Q value listed gives excitation energies of 16.623±0.010, 16.929±0.010, and 17.640±0.010 Mev.

$Be^9(He^3,\alpha)Be^8$ Reaction

A plot of the exposure taken at 70° with the $Be^9(He^3,\alpha)Be^8$ reaction is shown in Fig. 3. Groups which correspond to energy levels in Be^8 at 16.62, 16.92, and 17.64 Mev are clearly visible. In addition, a group from the $C^{12}(He^3,\alpha)C^{11}$ reaction appears. All groups are labeled with the symbol for the product nucleus.

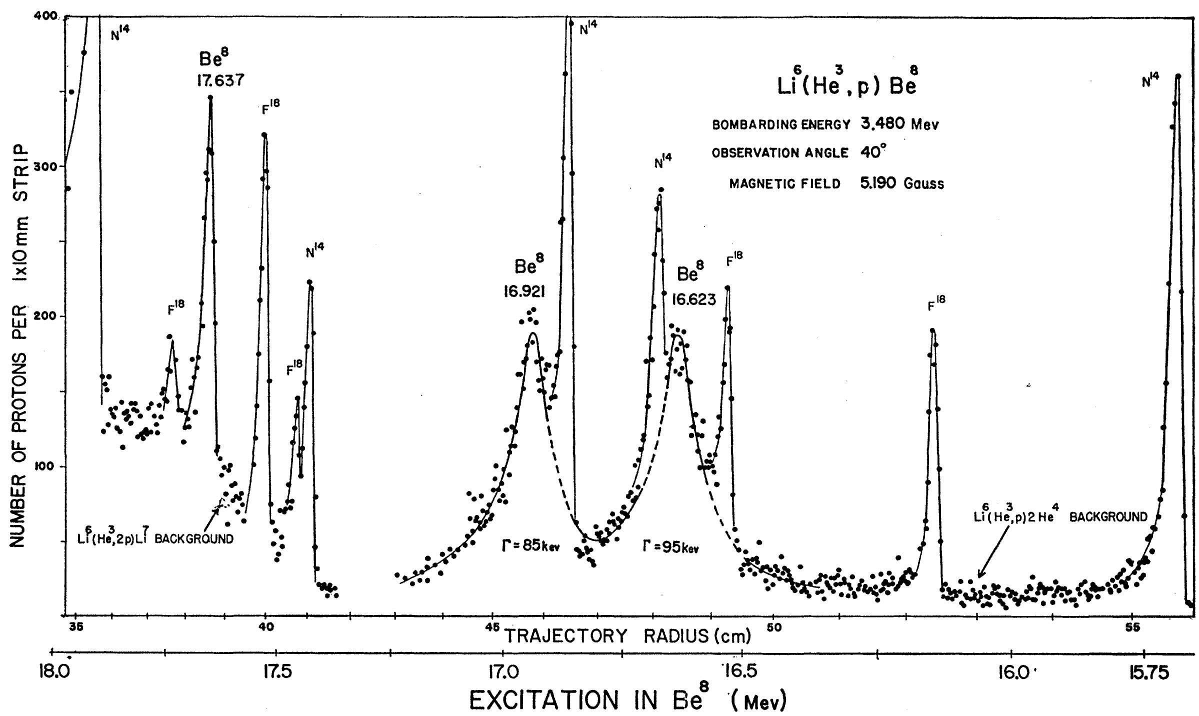

FIG. 2. Plot of a $Li^6(He^3,p)Be^8$ exposure which shows groups corresponding to energy levels in Be^8 at 16.623, 16.921, and 17.637 Mev. The other groups are produced by the $C^{12}(He^3,p)N^{14}$ and $O^{16}(He^3,p)F^{18}$ reactions. All groups are labeled with the symbol of the residual nucleus.

TABLE II. Q values and widths for the Be^8 levels observed with the $Li^6(He^3,p)Be^8$ reaction.

Observation angle (deg)	Bombarding energy (Mev)	16.62-Mev level Q value (Mev)	Γ (kev)	16.92-Mev level Q value (Mev)	Γ (kev)	17.64-Mev level Q value (Mev)
40	3.485	0.158±0.020	114±30			−0.853±0.015
60	3.485			−0.143±0.020	123±30	−0.851±0.015
80	3.485			−0.143±0.020	77±20	not sought
100	3.485	0.170±0.020	91±20			weak
60	3.999			−0.137±0.020	104±30	−0.855±0.015
60	4.233			−0.149±0.020	85±20	−0.857±0.015
90	4.233	0.161±0.020	83±20			obscured
Weighted mean		0.163±0.010	95±20	−0.143±0.010	85±20	−0.854±0.010

The Q values and widths of energy levels observed with the $Be^9(He^3,\alpha)Be^8$ reaction are given in Table III. If a ground-state Q value of 18.911 Mev is used,[14] the excitation energies of these levels are 16.625, 16.912, and 17.634 Mev. As only two runs were made with this reaction, these results are considered preliminary. Further work on this reaction is in progress.

Level Widths, Positions, and Intensities

A summary of Be^8 level structure between 14.5- and 18.0-Mev excitation, observed with the three reactions, appears in Table IV. A weighted mean of the excitation energies and widths measured with the three reactions is listed for each level.

The principal sources of uncertainty in the position measurements of Be^8 levels are the large natural widths of the levels and the small cross sections in the $B^{10}(d,\alpha)Be^8$ and $Li^6(He^3,p)Be^8$ reactions. The large natural width spreads the particle group along the plate over an area many times the usual size and reduces its height proportionately. To enhance the

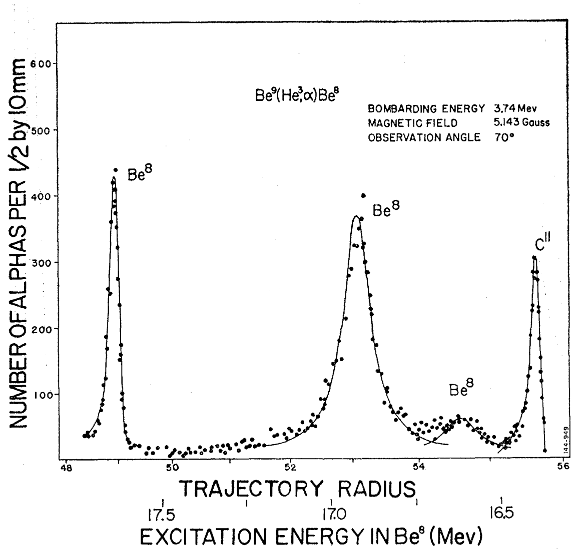

FIG. 3. Plot of a $Be^9(He^3,\alpha)Be^8$ exposure showing groups corresponding to energy levels in Be^8 at 16.623, 16.921, and 17.637 Mev. The group labeled C^{11} comes from the $C^{12}(He^3,\alpha)C^{11}$ reaction. The curves drawn through the two wide groups were derived from the Breit-Wigner single-level formula.

intensity, a number of changes were made which usually resulted in loss of resolution and accuracy. The beam spot size on the target was increased from $\frac{1}{2}$ mm in the vertical direction to $1\frac{1}{2}$ mm to permit greater beam currents. Thick targets were used to gain sufficient yield. In spite of these procedures, statistical fluctuations in the number of tracks per counting strip made the uncertainty in locating the position of the group on the plate a prominent source of error.

The uncertainty in Q values and excitation energies of the wide Be^8 levels is estimated to be 10 kev. The uncertainty in the width measurements is estimated as 20 kev. These estimates were checked by studying the positions of known reaction groups which appeared on the plates from the $B^{10}(d,t)B^9$, $O^{16}(d,\alpha)N^{14}$, $O^{16}(He^3,p)$-F^{18}, and $C^{12}(He^3,p)N^{14}$ reactions.

The ratio of the differential cross section of the reaction leading to the 16.62-Mev level to the differential cross section of the reaction leading to the 16.92-Mev level is listed in Table V for the $B^{10}(d,\alpha)Be^8$, $Li^6(He^3,p)Be^8$, and $Be^9(He^3,\alpha)Be^8$ reactions. The various bombarding energies and observation angles used are given in the table. The errors listed in the table are estimates obtained from the uncertainty in measuring the peak heights, that is, in obtaining the quantity σ_r used to find the total number of tracks in the group as discussed above. The ratio of differential cross sections is a significant quantity for measuring the operation of the isotopic-spin selection rule and its use is discussed below.

The absolute differential cross sections measured for the $B^{10}(d,\alpha)Be^8$ reaction leading to the 16.62- and 16.92-Mev Be^8 levels are listed in Table VI. Figure 4 shows the differential cross-section measurements made with the $Li^6(He^3,p)Be^8$ reaction. In the $Be^9(He^3,\alpha)Be^8$ reaction at 15° observation angle, the differential cross section leading to the 16.92-Mev level is estimated to be of the order of 50 mb/sr. This figure is based on the fact that the 16.92-Mev group had an intensity an order of magnitude greater than the same group from the $Li^6(He^3,p)Be^8$ reaction. The target thickness and exposures were roughly equivalent in these two reactions.

Since knowledge of the spins of both the 16.62- and 16.92-Mev Be^8 level is of considerable importance in the understanding of the selection rule violation, a

TABLE III. Q values and widths for the Be^8 levels observed with the $Be^9(He^3,\alpha)Be^8$ reaction.

Observation angle (deg)	Bombarding energy (Mev)	16.62-Mev level Q value (Mev)	16.62-Mev level Γ (kev)	16.92-Mev level Q value (Mev)	16.92-Mev level Γ (kev)	17.64-Mev level Q value (Mev)	17.64-Mev level Γ (kev)
15	3.733	2.292±0.018	95±30	1.998±0.015		1.278±0.015	<15
70	3.733	2.279±0.018	123±30	2.000±0.015	88±25	1.276±0.015	<15
Average		2.286±0.015	105±30	1.999±0.012	88±25	1.277±0.010	<15

TABLE IV. Summary of excitation energies and widths of Be^8 levels lying between 14.5 and 18.0 Mev observed in the present work.[a]

Reaction	16.62-Mev level excitation (Mev)	16.62-Mev level width (kev)	16.92-Mev level excitation (Mev)	16.92-Mev level width (kev)	17.64-Mev level excitation (Mev)	17.64-Mev level width (kev)
$B^{10}(d,\alpha)Be^8$	16.623±0.010	95±20	16.919±0.010	85±20	weak group	<20
$Li^6(He^3,p)Be^8$	16.623±0.010	95±20	16.929±0.010	85±20	17.640±0.010	<20
$Be^9(He^3,\alpha)Be^8$	16.625±0.015	105±30	16.912±0.012	88±25	17.634±0.010	<15
Weighted mean	16.623±0.010	95±20	16.921±0.010	85±20	17.637±0.006	<15

[a] Notes: 1. No level was seen near 16.08 Mev with either the $B^{10}(d,\alpha)Be^8$ or $Li^6(He^3,p)Be^8$ reaction. 2. No second level was seen near 17.7 Mev with any of the three reactions. See text for discussion. 3. The ground-state Q values used for the three reactions listed are 17.819, 16.786, and 18.911 Mev, respectively

measurement of the spin of the $T=0$ level of this pair is desirable. An attempt was made to use the speed of electromagnetic transitions to the 16.62- and 16.92-Mev levels as an indicator of the spin of these levels. Be^8 was produced in the spin-3 excited state at 19.22 Mev by bombarding Li^7 with protons. Electromagnetic transitions to the 16.62- and 16.92-Mev levels were sought by attempting to detect, with the spectrograph, the alpha particles from the decay of these two levels. The low-energy "tail" from the prolific $Li^7(p,2\alpha)$ reaction, however, obscured all of the alpha particles of interest. An upper limit of 1/300 of the intensity of the $Li^7(p,2\alpha)$ group was measured for the intensity of the alpha particles coming from the breakup of the 16.62- and 16.92-Mev Be^8 levels.

TABLE V. Ratio of the differential cross section for formation of the 16.62-Mev Be^8 level, to the differential cross section for formation of the 16.92-Mev level.

Observation angle (deg)	Bombarding energy (Mev)	Ratio of differential cross sections
	$B^{10}(d,\alpha)Be^8$	
35	4.00	1.26 ±0.34
50	4.00	1.80 ±0.70
70	4.00	1.45 ±0.64
90	4.00	0.76 ±0.47
110	4.00	1.11 ±0.56
35	3.86	1.46 ±0.45
50	3.86	1.40 ±0.46
35	4.22	1.44 ±0.36
	$Li^6(He^3,p)Be^8$	
20	3.50	1.45 ±0.24
40	3.50	1.25 ±0.26
60	3.50	1.67 ±0.56
80	3.50	1.87 ±0.68
	$Be^9(He^3,\alpha)Be^8$	
15	3.75	0.056±0.01
70	3.75	0.16 ±0.03

$Li^7(d,p)Li^8$ Reaction

No new energy level was observed between the ground state and the known level at 0.975-Mev excitation. A narrow level in this region of excitation would have been seen if it were 1/160 the intensity of the ground state. The presence of a level several hundred kev wide is not possible in Li^8 at this excitation, since a level here would be energetically stable against heavy-particle emission.

$C^{12}(He^3,p)N^{14}$ Reaction

On all the exposures taken with the $Li^6(He^3,p)Be^8$ reaction, groups were observed from the $C^{12}(He^3,p)N^{14}$ and $O^{16}(He^3,p)F^{18}$ reactions. The Q values of N^{14} energy levels between 5.6- and 6.5-Mev excitation measured in these exposures are listed in Table VII. If a ground-state Q value of 4.778±0.0015 Mev is assumed for the $C^{12}(He^3,p)N^{14}$ reaction,[15] the excitation energies for these levels are 5.691, 5.834, 6.203, and 6.440 Mev. These values are in excellent agreement with previous work[14] and for the latter two are considerably more precise. The limit of error for the Q-value measurements is estimated to be ±8 kev. No energy level was

TABLE VI. Differential cross sections for the $B^{10}(d,\alpha)Be^8$ reaction leading to energy levels at 16.62 and 16.92 Mev. Bombarding energy 4.0 Mev.

Observation angle (deg) (lab)	16.62-Mev level $d\sigma/d\Omega$ (mb/sr) (lab)	16.92-Mev level $d\sigma/d\Omega$ (mb/sr) (lab)
35	1.08±0.28	0.84±0.23
50	0.90±0.28	0.50±0.17
70	0.50±0.17	0.34±0.13

[15] R. K. Bardin, C. A. Barnes, W. A. Fowler, and P. A. Seeger, Phys. Rev. Letters 5, 323 (1960).

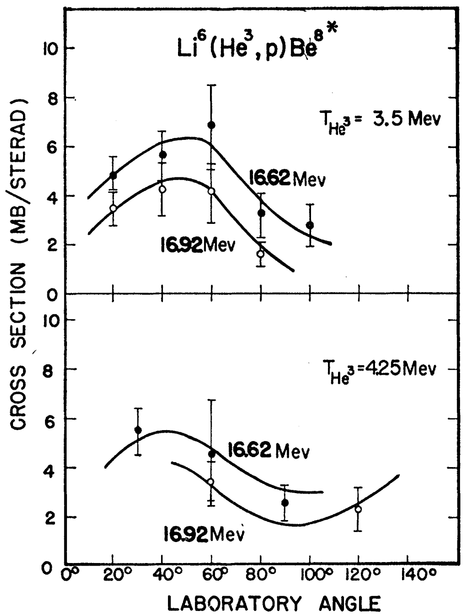

FIG. 4. Absolute differential cross sections of the $Li^6(He^3,p)Be^8$ reaction leading to the 16.623- and 16.921-Mev levels in Be^8. The cross sections are shown as a function of angle for bombarding energies of 3.50 and 4.25 Mev.

observed on any of the exposures at 5.98-Mev excitation. The level at 5.685-Mev excitation, however, was observed on many exposures, in disagreement with a recent report[16] in which this level was not observed with this reaction.

DISCUSSION

Be^8 Energy Level Structure

The data listed in Table IV are in considerable disagreement with earlier work on the excitation energies and widths of Be^8 energy levels. The level at 16.07 Mev reported by Slattery, Chapman, and Bonner,[6] using the $Li^7(d,n)Be^8$ reaction, is not seen. Bonner has suggested[17] that the wide bump which was thought to correspond to this energy level may be caused by the onset of a change in reaction mechanism at a certain bombarding energy rather than by a level in Be^8. The energy level at 16.67 Mev reported in this same study is probably the 16.623-Mev level observed in the present work. The $T=1$ assignment, however, becomes uncertain in view of the existence of another level, at only 300 kev higher excitation, which is firmly established by the present data. The group of neutrons ascribed to oxygen in the target may have concealed the 16.921-Mev level. The recent study of the $Li^7(d,n)Be^8$ reaction by Dietrich and Cranberg[8] confirms the existence of the 16.92-Mev level. They also fail to observe the levels at 16.07 and 17.7 Mev reported by earlier workers. In addition, their data establish the 16.62-Mev level as the lowest $T=1$ state. The detailed arguments for this last statement will be discussed below.

The work of Goward and Wilkins[9] on the $C^{12}(\gamma,\alpha)Be^8$ reaction shows a level at 16.9-Mev excitation in Be^8 and suggests energy levels at 16.5 and 17.7 Mev with intensities leading to them of about one quarter that for the 16.9-Mev level. The levels at 16.5 and 16.9 may correspond to the levels observed at 16.623 and 16.921 Mev in the present work. The level at 17.7 Mev is regarded by Goward and Wilkins as distinct from the level at 17.65 Mev which is well known from the $Li^7(p,\gamma)Be^8$ reaction. The 17.7-Mev level has not been observed with any of the three reactions used in the present work.

The energy level diagram for Be^8 deduced from all available data is shown in Fig. 5. The low-lying levels of the neighboring isobars are also shown to aid in the following discussion.

Spin and Parity

Information about the spin and parity of the 16.62- and 16.72-Mev levels can be deduced from the decay modes. The widths of nearly 100 kev indicate decay by particle emission, and only alpha-particle emission is energetically possible. Decay into two identical, spin zero particles can occur only from states of even spin and even parity.

The 16.62-Mev level, which is the lowest $T=1$ state, must be 2^+ by analogy with the Li^8 ground state. An upper limit for the spin of the other $(T=0)$ state is suggested by penetrability calculation. The probability for formation of a $J=2$ state relative to the probability

TABLE VII. Q values observed for the $C^{12}(He^3,p)N^{14}$ reaction

Run	5.68-Mev level Q (Mev)	5.83-Mev level Q (Mev)	6.23-Mev level Q (Mev)	6.44-Mev level Q (Mev)
1	-0.911 ± 0.010		-1.426 ± 0.010	
2		-1.052 ± 0.010	-1.423 ± 0.010	
3		-1.053 ± 0.010	-1.422 ± 0.010	-1.663 ± 0.010
4		-1.056 ± 0.010	-1.424 ± 0.010	-1.661 ± 0.010
5			-1.425 ± 0.010	
6	-0.915 ± 0.010	-1.061 ± 0.010	-1.433 ± 0.010	
7			-1.423 ± 0.010	
Average	-0.913 ± 0.008	-1.056 ± 0.008	-1.425 ± 0.008	-1.662 ± 0.008

[16] T. E. Young, G. C. Phillips, R. R. Spencer, and D. A. A. S. N. Rao, Phys. Rev. **116**, 962 (1959).
[17] T. W. Bonner (private communication).

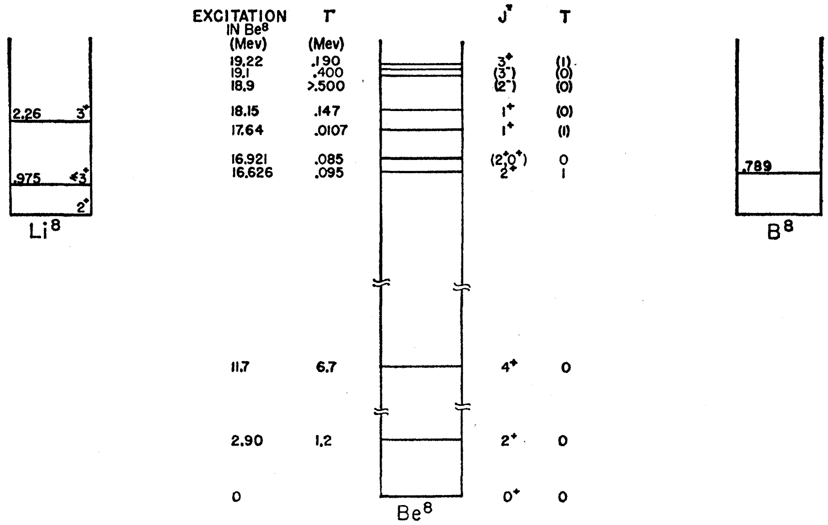

FIG. 5. Energy levels of the mass-8 isobars. The excitation energy, width, spin, parity, and isotopic spin for the Be^8 levels are given in the columns between the level diagrams. Parentheses indicate that the assignment is uncertain.

for formation of a $J=0$ or $J=4$ state in the $Li^6(He^3,p)$-Be^8 and $B^{10}(d,\alpha)Be^8$ reactions was calculated by the method of Hauser and Feshbach[18] which assumes levels of many spins and parities available in the compound nucleus. When a spin of 4 is assumed for the $T=0$ level the calculated yield ratio differs by more than an order of magnitude from that observed. A spin of 0 or 2 gives a result that is not in disagreement with the data. This suggests that the spin and parity of the $T=0$ levels is 0^+ or 2^+.

Excitation of the 16.62- and 16.92-Mev Levels in Be^8 through Direct Interaction Mechanisms

Important information for the understanding of the isotopic-spin selection rule violation in the $B^{10}(d,\alpha)Be^8$ reaction is obtained from pickup and stripping reactions leading to the 16.62- and 16-92-Mev levels in Be^8. The data given in Table V for the $Be^9(He^3,\alpha)Be^8$ reaction show that the yield to the 16.92-Mev level is about 10 times the yield to the 16.62-Mev level. The opposite behavior is shown by the $Li^7(d,n)Be^8$ reaction. Dietrich and Cranberg[8] found that in the $Li^7(d,n)Be^8$ reaction the 16.62-Mev level shows an $l=1$ stripping pattern, whereas the yield to the 16.92-Mev level is isotopic with an intensity about 1/25 the maximum intensity of the 16.62-Mev level. These large differences in behavior of the yields to the 16.62- and 16.92-Mev levels show that these eigenstates of Be^8 originate from rather different configurations and that these states are not strongly intermixed by the Coulomb or other interactions.

Another piece of information given by the direct interaction experiments is that the 16.92-Mev level is probably not the 2^+ $T=0$ level predicted by the intermediate-coupling shell model calculations of Kurath[19] which is supposed to lie slightly below the lowest $T=1$ level in Be^8. This predicted level arises from the ${}^3P^{[31]}$ state in L-S coupling. A study of the fractional parentage coefficients for extreme L-S coupling shows that Li^7 and a proton should readily couple to form all $P^{[31]}$ states. The isotropic angular distribution for the 16.92-Mev level observed by Dietrich and Cranberg in the stripping $Li^7(d,n)Be^8$ reaction suggests that the 16.92-Mev level is not related at all to the Li^7+p configuration and probably does not arise from the $P^{[31]}$ state. These arguments support a suggestion made by Kurath[20] that the 16.92-Mev level is a 0^+ $T=0$ level analogous to the 7.65-Mev level in C^{12} which apparently arises from an excited configuration.

Isotopic-Spin Selection Rule Violation

The aim of this experiment was to measure the extent of the isotopic-spin selection rule violation by comparing the yield to a $T=1$ level with the yield to a nearby $T=0$ level in both the $B^{10}(d,\alpha)Be^8$ and $Li^6(He^3,p)Be^8$ reactions. Operation of the selection rule should reduce the yield of the first reaction to the $T=1$ level but should not affect the second reaction. Before the levels at 16.62- and 16.92-Mev excitation in Be^8 can be used for this purpose, it must be established that one has $T=1$ and the other $T=0$.

Direct evidence for the position of the lowest $T=1$ level in Be^8 should come from the $C^{12}(\gamma,\alpha)Be^8$ reaction.[9] This reaction should feed the lowest $T=1$ level preferentially. The level seen most strongly is reported as being at 16.9 Mev. This seems to conflict with the present identification of the 16.62-Mev level as the lowest $T=1$ state and the 16.92-Mev level as $T=0$. The explanation of this discrepancy may lie in mis-

[18] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[19] D. Kurath, Phys. Rev. **101**, 216 (1956).

[20] D. Kurath (private communication).

identification of groups because of uncertainties in the range-energy relationships, low resolution, and difficulty in obtaining good statistics in the (γ,α) work. It is possible that the strong group seen actually leads to the 16.62-Mev level. Better evidence[21] comes from a combination of the β-decay end-point energies of Li^8 and Be^8 with the known mass differences. These data locate the lowest $T=1$ level near 16.8 Mev.

A possibility which must be considered is that both the 16.62- and 16.92-Mev levels are $T=0$ levels and that the lowest $T=1$ level has not yet been observed. To answer this objection we note that four different reactions have been used to study this region and that no other levels have been observed. Perhaps a better argument is that the observed absolute cross section and angular distribution of the 16.62-Mev level in the $Li^7(d,n)Be^8$ reaction[8] is just what is expected from the behavior of the analogous reaction $Li^7(d,p)Li^8$ ground state. It seems certain that the 16.62-Mev level is the lowest $T=1$ level. Clearly, some violation of the selection rule occurs as this level is excited with the $B^{10}(d,\alpha)Be^8$ reaction.

Before a comparison of yields to a $T=1$ and $T=0$ level can be made, it must further be established that both the 16.62- and 16.92-Mev levels are not $T=1$. The correspondence between energy levels in the mass-8 isobars supports this hypothesis. These energy levels are shown in Fig. 5. As every $T=1$ state in Be^8 must have an analog in Li^8 and B^8, the 16.62-Mev level would be expected to correspond to the Li^8 ground state and the 16.92-Mev level to the Li^8 first excited state at 975 kev if both Be^8 levels were $T=1$. This is unlikely, since the spacing of the Be^8 pair is only about $\frac{1}{3}$ the spacing between the ground state and first excited states in Li^8, as well as in B^8. In the unlikely event that an energy level in Li^8 near 300-kev excitation had been missed by other workers, this region of excitation was carefully reexamined with the $Li^7(d,p)Li^8$ reaction. As stated above, no new level was seen which would be analogous to the 16.92-Mev level in Be^8.

This spacing argument is not conclusive if the energy level positions in Li^8, Be^8, and B^8 are badly distorted for some reason. That this is not happening is suggested by the following argument: It is fairly certain that the 2.26-Mev, 3^+ state in Li^8 and the 19.22-Mev, 3^+ state in Be^8 are analogous levels. The correspondence in reduced widths between these states and other factors support this identification. Now, the 2.26-Mev spacing between the ground state and the 3^+ excited state in Li^8 agrees fairly well with the 2.60-Mev energy difference between the 3^+ level in Be^8 and the position of the lowest $T=1$ level. This agreement gives one confidence that there will be similar agreement in spacing between the Li^8 ground and first excited states and the Be^8 analogs of these levels and that the 16.92-Mev level in Be^8 is not the analog of the first excited state of Li^8 and hence does not have $T=1$.

Another argument against identifying the 16.92-Mev Be^8 level as analogous to the Li^8 first excited state is based on intermediate-coupling shell model calculations,[19] which predict that the first excited state in Li^8 is $J=1$. But, as stated above, the 16.92-Mev Be^8 level can only have an even spin. Therefore the first excited state in Li^8 cannot be identified with the 16.92-Mev Be^8 level (its analog is undoubtedly the 17.64-Mev Be^8 level). Thus it appears that the 16.92-Mev level has $T=0$. These arguments leave little doubt that the 16.62-Mev level is a $T=1$ level and that the 16.92-Mev level is a $T=0$ level.

The data showing the ratio of the differential cross section for formation of the $T=1$, 16.62-Mev level, to the differential cross section for formation of the $T=0$, 16.92-Mev level were given in Table V. It is to be noted that the ratio is nearly the same for both the $B^{10}(d,\alpha)Be^8$ and the $Li^6(He^3,p)Be^8$ reactions. One would expect, on the contrary, that the isotopic-spin selection rule should cause the ratio for the (d,α) reaction to be very much smaller than that for the (He^3,p) reaction. The fact that the ratios are nearly the same in both reactions indicates an almost complete violation of the selection rule.

Source of the Isotopic-Spin Selection Rule Violation

The large observed selection rule violation can originate from isotopic spin impurities in the initial or final states, or in the compound nucleus. These impurities are produced by the Coulomb interaction mixing states of different isotopic spin. It will be shown below that the experimental evidence points to the compound nucleus as the source of the violation in this reaction. Large isotopic spin impurities in the compound nucleus have been predicted by experiments on other (d,α) reactions, when due regard is paid to the effects of angular momentum and parity conservation.[5]

The initial state in the $B^{10}(d,\alpha)Be^8$ reaction is known to have only small isotopic spin impurities of the order of one part per thousand.[22] Much larger impurities, however, may exist in the final state. Large $T=0$ impurities in the Be^8 16.62-Mev $T=1$ level can be introduced by the Coulomb interaction if there is a neighboring state with the same spin and parity. At first sight, it appears that the 16.92-Mev $T=0$ level may be introducing large impurities into the 16.62-Mev state. However, this possibility is excluded by the very different behavior of the yields to these two levels in the $Be^9(He^3,\alpha)Be^8$ and $Li^7(d,n)Be^8$ reactions. The next closest state which may have the same total angular momentum and parity as the 16.62-Mev level is the $T=0$ state at 19.9-Mev excitation. However, this state will introduce an impurity of at most a few percent in

[21] W. E. Burcham, *Progress in Nuclear Physics* (Pergamon Press, New York, 1955), Vol. 4, p. 191.

[22] W. M. MacDonald, Phys. Rev. **101**, 271 (1956).

intensity if a very generous Coulomb interaction of 500 kev is assumed. A much larger impurity than this is needed to understand the strong selection rule violation as coming from final state impurities.

Another possible explanation of the large selection rule violation is that the 16.62-Mev level has the properties of a "threshold" level as proposed by Baz.[23] According to this theory, non-charge-invariant "threshold" states may occur near two-particle thresholds because of the existence of a static potential between a nucleon and the nucleus. If the 16.62-Mev Be^8 level had this non-charge-invariant property, the near-equal yield of this $T=1$ level compared to the adjacent $T=0$ level in both the $B^{10}(d,\alpha)Be^8$ and $Li^6(He^3,p)Be^8$ reactions could be readily explained. This possibility does not appear as a likely explanation of the selection rule violation. If the 16.62-Mev level were a threshold state, we would expect an abnormally large reduced width in the $Li^7(d,n)Be^8$ stripping reaction leading to this level. However, the reduced width for this level does not show an anomalous size, but forms a consistent picture with the other reduced widths of the $T=1$ levels in the mass-8 isobars.

An extraction of the reduced widths from the data of Dietrich and Cranberg was made using the Butler-Born approximation stripping theory as given by Macfarlane and French.[24] Using a Butler radius of 4.2 f and a bombarding energy of 7.25 Mev, the values of the absolute reduced width, θ^2, for the 16.62- and 17.64-Mev levels are 0.023 and 0.014, respectively. An $l=1$ stripping pattern has been assumed for the 17.64-Mev level. For the analogous reaction $Li^7(d,p)Li^8$, Macfarlane and French list θ^2 as 0.053 and 0.028 for the ground state and first excited state. If charge independence were strictly obeyed, the reduced widths in the $Li^7(d,n)Be^8$ reaction should be $\frac{1}{2}$ the reduced widths in the $Li(d,p)Li^8$ reaction. Experimentally, the reduced widths in the $Li^7(d,n)Be^8$ reaction are about $\frac{1}{2}$ the corresponding reduced widths in the $Li^7(d,p)Li^8$ reaction. This agreement seems surprisingly good since the accuracy of the simple Butler formula in extracting the reduced widths is questionable. However, a more reliable test is to compare the ratio of the reduced widths of the two states between the (d,n) and (d,p) reactions. In this way, the uncertainties introduced by the Born approximation and the neglect of Coulomb effects should be minimized. The ratio of reduced widths in the $Li^7(d,p)$-Li^8 reaction of the first excited state to the ground state is 0.53. In the $Li^7(d,n)Be^8$ reaction, the corresponding ratio between the 17.64-Mev state and the 16.64-Mev state is 0.59. If the 16.62-Mev Be^8 level were a true "threshold" state, the proton reduced width for this state would be abnormally large. This effect would change the reduced widths' ratio for the $Li^7(d,n)Be^8$ reaction below the value of 0.53 measured in the $Li^7(d,p)Li^8$ reaction. This behavior is not observed. Of course, the 17.64-Mev Be^8 level could also be a "threshold" state to the extent which would cancel the effect on the reduced width ratio. This possibility, however, seems a bit fortuitous. Therefore it seems that the 16.62-Mev level does not show an expected property of a "threshold" state.

Although the above argument depends on the consistency of the Butler-Born approximation in extracting reduced widths, the argument does seem to be fairly good evidence that isotopic spin is a good quantum number for the 16.62-Mev $T=1$ level in Be^8. Consequently, the source of the strong selection rule violation is probably not isotopic spin impurity in the final state, but rather impurities in the compound nucleus.

In summary, we have found that the yields to the 16.62-Mev $T=1$ and 16.92-Mev $T=0$ levels in Be^8 are nearly equal in both the $B^{10}(d,\alpha)Be^8$ and $Li(He^3,p)$-Be^8 reactions. Isotopic spin considerations, however, should forbid the formation of $T=1$ levels with the $B^{10}(d,\alpha)Be^8$ reaction. Arguments have been given which suggest that initial or final state isotopic spin impurities do not account for this behavior. Therefore, the compound nucleus is suspected as the source of the complete failure of the isotopic spin selection rule.

The present work supports the suggestion that the isotopic-spin selection rule has little effect in (d,α) reactions and that the apparent effect previously observed in many reactions was rather caused by statistical weight factors for the special case of 0^+ initial and final states. In other charged particle reactions such as (d,d') or (α,α') where the selection rule has been shown to work, the reactions probably do not proceed primarily through the compound nucleus but rather by means of a direct interaction. In such a reaction Coulomb forces do not have time to act and the isotopic spin is conserved.

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[23] A. I. Baz, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1959), Vol. 8, p. 349, and *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960), p. 341

[24] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).