In this respect the calculation should serve for comparison of the hypotheses of weak or strong spin-orbit coupling. The chief points for comparison of the models are the angular momenta (spins) and magnetic moments of the ground states and the four-shell structure of the binding energy curve. In comparing the spins with experiment both models give some incorrect values, and neither is to be preferred over the other. The magnetic moments are generally somewhat better for the jj model. From the binding energy curve, the LS model seems preferable since it contains a pronounced four-structure. It is possible that there is a transition from LS coupling in the early part of the shell to jj coupling in the latter part, which would remove most of the spin difficulties and not affect the binding energies seriously. The present influx of experimental data on energy levels of the $1p$-shell nuclei should help greatly to clarify the problem.

The author wishes to express his appreciation to Professor M. G. Mayer for discussion and guidance in the course of this work.

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Electrostatic Analysis of Nuclear Reaction Energies. II*

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Electrostatic analysis of incident and product particle energies has been used to measure the following ground state Q-values: $O^{16}(d,\alpha)N^{14}$ (3.113±0.0035 Mev), $B^{10}(p,He^3)Be^8$ (−0.536±0.003 Mev), and $B^{10}(p,\alpha)Be^7$ (1.147±0.0025 Mev). The energy of the lowest level in B^{10} has been determined to be 719±1.6 kev; that of Be^7 to be 429±3 kev. Approximate cross sections are given for the above reactions and upper limits for $O^{16}(d,\alpha)N^{14*}$ (2.3-Mev level), and for $B^{10}(p,p')B^{10*}$ (2.1- and 1.7-Mev levels).

I. INTRODUCTION

FURTHER accurate measurements of nuclear Q-values have been made using the equipment and procedure described in earlier articles.[1,2] It will suffice here to say that a cylindrical electrostatic analyzer[3] was used for measuring the energy of the bombarding particles (T_1), and a spherical electrostatic analyzer[1] for measuring the energy of the product particles (T_2). A redetermination of the angle of observation with respect to the incoming beam, necessitated by a realignment of the spherical analyzer collimating apertures, was made using the measured positions of the apertures as described previously,[1] and by scattering deuterons from Li^6. The mean angle was found to be 134°33′±3′.

The nichrome resistor stack used in our earlier measurements was replaced with a new stack consisting of sixty one-megohm Shallcross Evenohm resistors, Type BX116E, whose temperature coefficient is less than 0.002 percent/°C. These were mounted with corona shields inside Lucite cylinders in which dried air was circulated by a blower. Several low voltage taps were provided to facilitate regulating and measuring the voltage over a wide range of values.

Several appendices are included with this paper. The first one consists of errata to paper I.[2] The second displays the form of the relativistic correction terms used in I and in II. The third appendix is concerned with the masses used in the calculations.

II. RESULTS AND DISCUSSION

$O^{16}(d,\alpha)N^{14}$

This Q-value is an important link in the group of reactions used by Li *et al.*,[4] in determining the masses of the light nuclei, as it is the only convenient connection to O^{16}, the standard of atomic masses.

Two determinations of this Q-value were made. The first was made using a target of 0.001-inch aluminum foil which had been heated in air to form the oxide. Because of the thickness of the aluminum it was impossible to scatter deuterons from the target in order to check the amount of contamination and the amount of oxygen. The observed counting rates of the doubly ionized alpha-particles are shown in Fig. 1. For a second run a target of beryllium oxide was prepared by heating in air a thick tantalum foil onto which had been evaporated beryllium. Since these targets were used immediately after putting them into the analyzer, it is reasonable to assume that the contamination on them is negligible. The rate at which carbon is deposited on a 1000A Ni foil was checked during the present measurements, and over a six-and-a-half-hour period of bombardment with a beam of the same magnitude as that used

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* Supported by the Wisconsin Alumni Research Foundation and the AEC.

† Now with Atomic Energy of Canada, Ltd., Chalk River, Ontario, Canada.

[1] Browne, Craig, and Williamson, Rev. Sci. Instr. **22**, 952 (1951).

[2] Williamson, Browne, Craig, and Donahue, Phys. Rev. 84, 731 (1951). This article will be referred to as I.

[3] Warren, Powell, and Herb, Rev. Sci. Instr. **18**, 559 (1947).

[4] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

throughout this work, 0.2 microamperes, less than 0.01-kev thickness of carbon for a 1-Mev proton was deposited. This slow rate of build-up may be attributed to the fact that the targets were maintained at about 200°C, and that a triple-collision, liquid-air-cooled baffle was kept over the diffusion pump. The results for the two targets are as follows:

Target	Bombarding voltage (T_1) in Mev	Q (Mev)
Al_2O_3	0.893	3.1125±0.0035
BeO	0.847	3.1133±0.0035
	Average value:	3.113 ±0.0035

Table I displays the component errors determining the uncertainty in the values quoted above. The differential cross section at 134°33′ is of the order of 9×10^{-27} cm^2 per steradian.

The individual values are in agreement with the values of 3.112±0.006 Mev,[5] and 3.119±0.005 Mev,[4] as determined at the Massachusetts Institute of Technology and the California Institute of Technology, respectively.

$O^{16}(d,\alpha)N^{14*}$(2.3-Mev level)

Alpha-particles going to a level in N^{14} with an excitation energy between 2.0 and 2.8 Mev were undetected when using a deuteron energy of 2.877 Mev. Assuming a target of Al_2O_3, the differential cross section must be less than 1.4×10^{-27} cm^2/steradian; otherwise, this level would have been detected. This result is in agreement with work of Ashmore and Raffle,[6] and Burrows *et al.*,[7] who did not see any alpha-particles corresponding to this level when O^{16} was bombarded with 6.8- and 8-Mev deuterons, respectively.‡

Table I. Tabulation of errors for the $O^{16}(d,\alpha)N^{14}$ reaction energy. $Q=3.113\pm0.0035$, T_1 (deuteron energy) = 0.8933 Mev, T_2 (alpha energy) = 2.6729 Mev.

Source of error	Magnitude	Error in Q Mev
Relative calibration of	±0.03 percent of T_1	0.0002
the analyzers	±0.03 percent of T_2	0.0011
Angle of observation	±3′	0.0004
Location of half-value of alpha-edge	±0.0006 Mev	0.0008
Absolute calibration of $Li^7(p,n)Be^7$ threshold	±0.1 percent of Q	0.0031
Limit of error of measurement (dQ_m)[a]		0.0025
Total limit of error[a]		0.0056
Total probable error[a]		0.0035

[a] Notation as in reference 2: "limits of error" $=\Sigma_i|\epsilon_i|$, and probable error $=(\Sigma_i\epsilon_i^2)^{\frac{1}{2}}$.

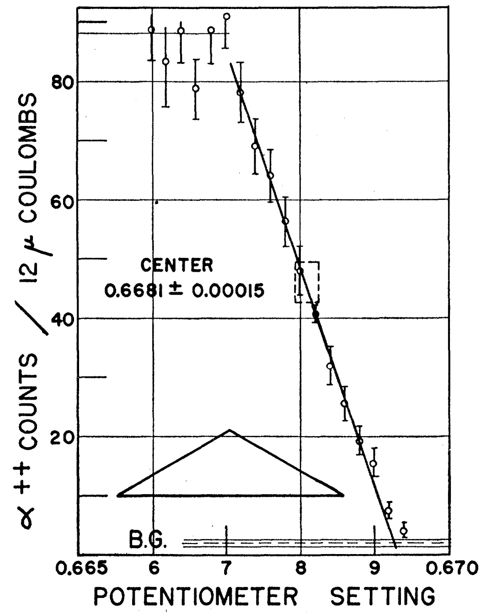

Fig. 1. Doubly ionized alphas from $O^{16}(d,\alpha)N^{14}$. The bombarding energy is 0.893 Mev. The potentiometer setting is approximately $\frac{1}{4}$ alpha-energy.

The low upper limit on this cross section is compatible with isotopic spin selection rules imposed by the assumption of charge independence of nuclear forces. Adair[8] discusses this subject more fully in a forthcoming publication. It should be pointed out, however, that the spins of the ground state and the 2.3-Mev level are expected to differ by one unit of angular momentum; thus even from the requirement of conservation of spin and parity the yield to this level would be expected to be less than to the ground state.

B^{10} Reactions

The same B^{10} target was used for each of the following reactions. It consisted of a boron layer, approximately 4 kev thick for protons of 0.94 Mev, evaporated onto a 1000A Ni backing. The exact composition of this target is uncertain, but scattered protons indicated that it contained considerable oxygen. The nitrogen content was not checked; however, our experience with other boron targets indicates that some nitrogen may be present. Since the composition of the target is so uncertain, the differential cross sections given are only an indication of the order of magnitude, assuming B_2O_3 targets. The boron, obtained from the AEC, was approximately 96 percent B^{10}. It was possible to check for carbon build-up by elastically scattering protons. Since this target was in the analyzer for many days, carbon build-up occurred, necessitating a small correction to the Q-values of all B^{10} reactions.

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[5] Straight, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[6] A. Ashmore and J. F. Raffle, Proc. Phys. Soc. (London) **A64**, 754 (1951).

[7] Burrows, Powell, and Rotblatt, Proc. Roy. Soc. (London) **A209**, 478 (1951).

‡ Recent work by Van de Graaff, Sperduto, Buechner, and Enge (Phys. Rev. **86**, 966 (1952)) using 2-Mev deuterons on O^{16} also gave no indication of alpha-particles corresponding to N^{14} being left in an excited state.

[8] R. K. Adair, Phys. Rev. **87**, 1041 (1952).

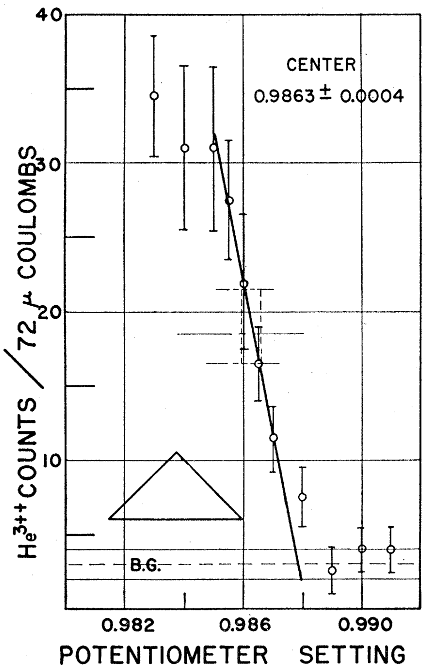

FIG. 2. Doubly ionized He^3 from $B^{10}(p, He^3)Be^8$. The bombarding energy is 3.421 Mev. The potentiometer setting is approximately $\frac{3}{4}$ He^3 energy.

$B^{10}(p,He^3)Be^8$

Edges were taken using protons of 3.421 and 3.216 Mev. The observed counting rates of the doubly ionized He^3 are shown in Fig. 2, for 3.421-Mev protons. Since a change in bombarding energy (T_1) will cause a change in the energy of the reaction product (T_2), with the amount dependent on the particular reaction, the agreement in the Q-values, -0.536 ± 0.003 and -0.535 ± 0.004 Mev, is a check that the particles being measured were from this reaction. A contamination correction of 1 ± 0.5 kev has been applied to T_2. The differential cross section at 134°33 is of the order of 1×10^{-27} cm^2/steradian. The Q-value is -0.536 ± 0.003 Mev probable error; ±0.004 Mev limit of error.

There are no other observations of this reaction. However, its Q value can be calculated from other reaction cycles. For example, a value of -0.536 ± 0.008 Mev is obtained from the following cycle[9]: $Li^7(p,n)Be^7$, $Be^9(d,\alpha)Li^7$, $Be^9(p,d)Be^8$, $D(d,p)T$, $T(\beta^-)He^3$, H^1-n, and $B^{10}(p,\alpha)Be^7$.

$B^{10}(p,\alpha)Be^7$

Using a bombarding energy of 3.333 Mev a Q-value of 1.147 ± 0.0025 Mev probable error, ±0.0044 Mev limit of error, was found. A contamination correction of 0.6 ± 0.3 kev has been included. This value is in agreement with the values of 1.148 ± 0.006 (California Institute of Technology),[10] 1.152 ± 0.004 (MIT),[11] and 1.147 ± 0.010 (Cambridge).[12] The differential cross section is of the order of 2×10^{-26} cm^2/steradian.

$B^{10}(p,\alpha)Be^{7*}$

Three determinations of this Q-value were made and are listed in Table II. The first two have a carbon correction of 0.6 ± 0.15 kev applied to T_2 and the latter 0.5 ± 0.15 kev. The differential cross section is of the order of 1×10^{-26} cm^2/steradian.

On subtracting the average of these Q-values (0.718 Mev), from that for the ground state, a value of 429 ± 3 kev is obtained for the first level in Be^7. This value is in agreement with the values summarized by Brown *et al.*,[10] and the more recent measurements of Johnson and Barschall[13] (431 ± 5 kev), but does not quite overlap that of Willard and Preston[14] (434 ± 1 kev with no assigned error due to calibration).

$B^{10}(p,p')B^{10*}$(719-kev level)

The energy of the lowest detected level in B^{10} was measured by the inelastic scattering of protons to be 719 ± 1.6 kev probable error, ±3 kev limit of error. The observed counting rates of the protons are shown in Fig. 3. The bombarding protons had an energy of 2.191 Mev, at which energy the differential cross section was of the order of 3×10^{-27} cm^2/steradian.

The value of 719 ± 1.6 kev agrees with the California Institute of Technology values of 716.6 ± 1 kev[15] and 718 ± 5 kev,[16] obtained by measuring the energy of the gamma-rays from Be^9 $(d,n)B^{10*}$ and $B^{10}(p,p')B^{10*}$, respectively. Rasmussen *et al.*, applied a Doppler correction to their measured value of 716.6 kev, yielding a final value of 713 ± 1.5 kev. However, some doubt existed as to the necessity of this correction,[17] and our value indicates that no correction is necessary. Therefore, the lifetime for gamma-emission must be longer than the time required to stop the recoiling B^{10} nucleus ($\sim10^{-13}$ sec).

TABLE II.

T_1 Mev	Q Mev	dQ_m Mev	dQ limit Mev	dQ probable Mev
3.333	0.717	0.0036	0.0043	0.0026
3.333	0.717	0.0036	0.0043	0.0026
1.460	0.720	0.002	0.003	0.002

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[9] Suggested by Dr. D. M. Van Patter in a private communication.

[10] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).

[11] Van Patter, Sperduto, Strait, and Buechner, Phys. Rev. **79**, 900 (1950).

[12] W. E. Burcham and J. M. Freeman, Phil. Mag. **41**, 337 (1950).

[13] C. H. Johnson and H. H. Barschall, Phys. Rev. **81**, 317 (1951).

[14] H. B. Willard and W. M. Preston, Phys. Rev. **81**, 480 (1951).

[15] Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).

[16] R. B. Day and T. Huus, Phys. Rev. **85**, 761 (1952).

[17] V. K. Rasmussen, Ph.D. thesis, California Institute of Technology (1950) (unpublished).

Other Levels in B^{10}

Despite an extensive search at several bombarding energies, ranging up to 4.2 Mev, no inelastically scattered protons from higher levels in B^{10} were observed. Therefore, at these bombarding energies, an upper limit of about 3×10^{-28} cm^2 per steradian for other inelastic scattering cross sections is indicated.

The authors wish to thank Professor H. T. Richards for suggesting this work and for his subsequent advice. Messrs. M. T. McEllistrem and R. E. Benenson helped in part of the experimental work. Dr. Fay Ajzenberg provided the Li^6 target.

APPENDIX

A. Errata to I [Phys. Rev. 84, 731 (1951)][2]

1. Fig. 2: The ordinates should read *P* counts per 0.2 microcoulomb, instead of per 0.1 microcoulomb.
2. Recalculation of the contamination corrections to the Q-values for the $Be^9(p,\alpha)Li^6$ reaction, when the Li^{6++} and Li^{6+++} particles were observed, gives values of 2.126 and 2.127 Mev, respectively, in line with the other measurements.

B. Relativistic Correction Terms

Dr. R. M. Williamson (Ph.D. thesis, University of Wisconsin, unpublished) has expressed the energy of the recoil particle in terms of the classical expression plus a correction term which is obtained when the relativistic expression for momentum is used,

$$\text{Recoil energy } (T_3)=1/M_3[M_1T_1+M_2T_2-2(M_1M_2T_1T_2)^{\frac{1}{2}}\cos\theta]+V,$$

where the relativistic correction V is given by

$$V=\frac{1}{2E_3}\left[T_1^2+T_2^2-T_3^2-\cos\theta(E_1E_2T_1T_2)^{\frac{1}{2}}\left(\frac{T_1}{E_1}+\frac{T_2}{E_2}\right)\right],$$

correct to the first power of T/E.

The energy of particles of mass M_1 elastically scattered from target nuclei of mass M_0 through an angle θ is given by

$$\frac{T_2}{T_1}=\left(\frac{M_1}{M_1+M_0}\cos\theta+\left\{\frac{M_0-M_1}{M_0+M_1}+\left(\frac{M_1}{M_1+M_0}\right)^2\cos^2\theta-L\right\}^{\frac{1}{2}}\right)^2,$$

where

$$L=\frac{T_2'}{E_0}-\frac{\cos\theta}{2E_0}\left(\frac{T_2'}{T_1}\right)^{\frac{1}{2}}(T_1+T_2')$$

is the relativistic correction calculated to the first power of T/E.

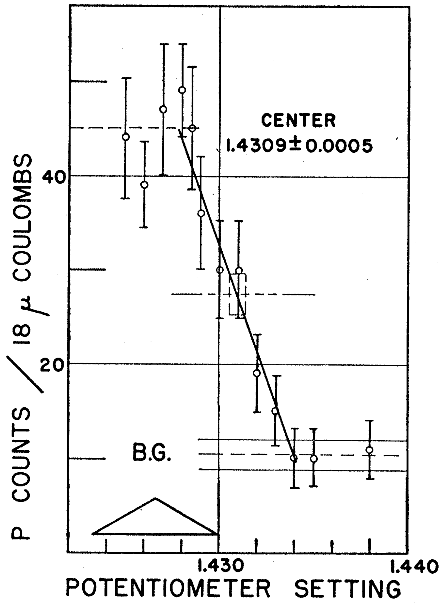

FIG. 3. Protons from $B^{10}(p,p')B^{10*}$ (719-kev level). The bombarding energy is 2.191 Mev. The potentiometer setting is approximately $\frac{3}{2}$ proton energy.

Subscripts 0, 1, 2, and 3 refer to the target, bombarding, measured product, and recoil particles, respectively; T is the energy of the particle; M is the mass; $E=Mc^2$; θ is the angle between incident and product particles; and T_2' is the energy obtained using the formula with no relativistic correction.

C. Masses Used

Nuclear masses were used for M_1 and M_2. The mass used for the recoil particle M_3 was its nuclear mass plus the mass of the electrons carried along with it. The number of electrons attached to the recoiling nucleus was estimated by comparing the orbital velocities of the electrons with the linear velocity of the nucleus, as is discussed by Bohr in "The Penetration of Atomic Particles Through Matter".[18]

The error introduced in the Q-values by neglecting the electrons accompanying the recoil particle reactions would be less than 0.5 kev.

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[18] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 18, No. 8 (1948).