revised Feather relationship[27]

$$E=1.92R^{0.725}\quad\begin{cases}E \text{ in Mev}\\ R<0.3\ \text{g/cm}^2\ \text{Al.}\end{cases}\qquad(4)$$

From this equation the energy of Tc^{99} is found to be 0.312 Mev, which agrees well with spectrographic values of 0.309 Mev[28] and 0.30±0.1 Mev.[29]

[27] L. E. Glendenin and C. D. Coryell, "The relationship between the range and spectrograph energy of beta particles," paper 11, *Radiochemical Studies; The Fission Products* (McGraw-Hill Book Company, Inc., New York, to be published), National Nuclear Energy Series, Division IV, Vol. 9B; Nucleonics 2, 12 (January, 1948).

[28] M. Freedman and F. Wagner (to be published).

[29] B. H. Ketelle and J. W. Ruch, Phys. Rev. **77**, 565 (1950).

Previous results based on measurements of the initial half-thickness of the absorption curve, or on Feather analyses were 0.3 Mev,[2,3] 0.32 Mev,[4,5] and 0.31±0.03 Mev.[25]

The absorption measurements showed that the ratio of beta- to gamma-counting rates was greater than 20,000, which corroborates the previous measurements[3–5] indicating no gamma-ray. These results indicate less than 1 gamma-ray per 100 beta-particles.

We wish to express our gratitude to Mr. Laurence Sjoblom, Mrs. Marilyn Sietsema, Mrs. R. Hospelhorn, and particularly Mr. Jerome Lerner, who aided us at various stages of the measurements.

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The Reaction Energies of Light Nuclei from Magnetic Analysis*

E. N. STRAIT,† D. M. VAN PATTER, W. W. BUECHNER, AND A. SPERDUTO

Physics Department and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

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An extensive survey has been made of the reaction energies of ground-state transitions induced by proton and deuteron bombardment of light nuclei. A total of nineteen stable nuclei from deuterium through sulfur was investigated, and the Q-values directly measured for thirty-eight different reactions. From these Q-values, the energy releases of a number of other reactions have been computed. The reactions studied include the (p, α), (d, p), and (d, α); and the individual Q-values have been determined to precisions that are between 0.08 and 0.25 percent. The reaction products were analyzed by means of 180-degree focusing in the field of a large annular magnet.

The Q-values measured include those of a series of nuclear reactions which directly connect the mass of the alpha-particle with the deuteron mass and O^{16}. From these measurements, the mass of the alpha-particle has been determined as 4.003865±0.000007 amu.

I. INTRODUCTION

UNTIL the last few years measurements of the reaction energies of ground-state transitions involving charged particles were confined to range methods where the precision available was generally not better than 100 kev. In many cases the results of these measurements have been used to establish the masses of the nuclei involved in the reactions. However, magnetic analysis, as opposed to range measurements, makes possible an improvement in precision of approximately a factor of 10, with an attendant improvement in the accuracy to which masses can be established.

In 1947, a high resolution analyzing system was constructed at the M. I. T. High Voltage Laboratory for the specific purpose of determining Q-values of nuclear reactions to a high precision.[1] This consisted of a 90-degree deflecting magnet for analysis of the bombarding deuterons or protons and a large annular magnet for 180-degree focusing of the reaction products. During 1948 and 1949, a number of reaction energies were measured with greater accuracy than previously reported. The reactions investigated were as follows:[2–4] $Li^6(d, p)Li^7$ and $Li^7(d, p)Li^8$; $Be^9(d, \alpha)Li^7$ and $Be^9(d, p)Be^{10}$; and $C^{12}(d, p)C^{13}$ and $O^{16}(d, p)O^{17}$. During the past year, these investigations have been extended to a survey of over thirty-five reactions involving target nuclei from D^2 to S^{32}, including remeasurements of the reactions already reported. In some of these reactions, the ground-state group has not been previously observed. This paper will be confined to a report of the results on the ground-state transitions. The results on transitions to excited states of the residual nuclei will be described in other publications, some of which have already appeared in print.[5,6]

* A report of these measurements was made at the Chicago Meeting of the American Physical Society, November, 1950. Phys. Rev. **81**, 315 (1951).

† Now at Northwestern University, Evanston, Illinois.

[1] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

[2] E. N. Strait and W. W. Buechner, Phys. Rev. **76**, 1766 (1949).

[3] W. W. Buechner and E. N. Strait, Phys. Rev. **76**, 1547 (1949).

[4] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[5] Buechner, Van Patter, Strait, and Sperduto, Phys. Rev. **79**, 262 (1950).

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

II. EXPERIMENTAL PROCEDURE

While the apparatus and experimental techniques employed in these investigations were essentially similar to those described in previous papers,[1–6] a number of improvements in the methods for obtaining and analyzing the data have been incorporated, which increase the precision of the energy measurements. These changes in apparatus and techniques are described below.

In the results reported in some of the above papers,[1–4] the uncertainties in the fundamental constants used to make the conversion from observed Hr values to particle energies and the uncertainty of the Rosenblum and Dupouy[7] value for Hr of polonium alpha-particles used to calibrate our fluxmeter[4] led to uncertainties of the order of 2.5 in 10^3 in the particle energies. By adopting DuMond's value[8] of 9652.2 ± 0.7 emu/gram for the Faraday and using exact masses for the proton, deuteron, alpha-particle, and so forth, the uncertainty in the particle energies arising from conversion from observed Hr to energy has been reduced to about 7 parts in 10^5.

Rutherford and his collaborators[9] made careful measurements of the relative velocities of alpha-particles from various radioactive sources. They found the velocity of polonium alphas to be 0.83100 that of RaC′ alphas, with an accuracy of 2 in 10^4. Briggs' value[10] for Hr of RaC′ alpha-particles is 3.99277×10^5 absolute emu to within 4 parts in 10^5. A combination of these results, together with appropriate relativity factors, gives a value of 3.3159×10^5 gauss centimeters (abs. emu), accurate to 1 part in 5000, for polonium alpha-particles. Heretofore, we have used Rosenblum's value of 3.3158×10^5 gauss centimeters, which had an uncertainty of 1 part in 1000. While no change in our previously reported energy values is required because of this change, the uncertainty in the measurements arising from the standard used for fluxmeter calibration has been reduced to 4 parts in 10^4.

A precise measurement has been made of the angle which the incident ion beam makes with the median plane of the annular magnet. Previously, this angle was known only to be within the limits imposed by the collimating system for the ion beam. These limits were necessarily rather wide for reasons of beam intensity. This is the angle with respect to the incident beam at which particle energies are observed; and, since an uncertainty δ in its value causes in the reaction energy an uncertainty $\Delta Q=2(M_1M_2E_1E_2)^{\frac{1}{2}}\delta/M_3$, it is necessary for precise results that δ be small. M_1, M_2, E_1, and E_2 are the masses and energies of the incident and emitted particles, respectively, and M_3 is the mass of the residual nucleus.[11]

To measure the angle of observation, an extension tube about 6 feet in length was placed at the ion-beam exit from the annular magnet and a proton beam was allowed to pass through the target chamber and impinge on a quartz disk at the far end of the tube. Appropriate cross hairs and narrow collimating slits made it possible to measure accurately the beam direction. Measurements were also made on the effect of the fringing field of the annular magnet at various field strengths over the range normally used for the study of reaction energies. The angle of observation was found to take on values from $(\frac{1}{2}\pi-0.0029)$ radians at zero field to $(\frac{1}{2}\pi-0.0015)$ radians at maximum field. The uncertainty, δ, varied from ±0.0007 radian at zero field to ±0.0002 radians at maximum field. The terms 0.0029 radian to 0.0015 radian represent the deviation from 90 degrees and are now applied as correction terms in the calculation of Q-values. The uncertainty, δ, is smaller by at least a factor of 10 than before and now contributes less than 1 kev to the uncertainties that must be placed on the measured reaction energies.

Calculations have been made that permit corrections for the effect of the finite acceptance angle (approximately 0.004 radian either side of the median plane) that the collector (nuclear-track plate) subtends at the target and also for the width of the portion of the target illuminated by the incident ion beam. The results of the calculations have been verified experimentally by observations of the peak shape and position as determined from counting different areas of the same plate. These corrections amount to about 1.5 kev in the cases of the more sensitive reactions, which are characterized by high Q-values and light residual nuclei. The uncertainty in such a correction, arising from the uncertainty in peak shape, is a fraction of a kilovolt.

The relative location of the alpha-particle source used for fluxmeter calibration and of the position of the beam on the target has been remeasured with improved precision. This relationship is of interest, since it is of considerably greater importance in translating fluxmeter readings into evaluations of Hr than is the full diameter of the magnet itself. To make this measurement, a nuclear-track plate was placed in a small holder in the target position and was bombarded with deuterons from the generator. In order to keep the exposure low enough to permit observation of track distribution, the emulsion was covered with an aluminum foil of appropriate thickness to stop the deuterons but to permit passage of protons from $Al^{27}(d, p)Al^{28}$. The track distribution was found to have a shape nearly identical to that obtained for thin-target reaction products focused by the analyzing magnet. This demonstrates, incidentally, the absence of any serious focusing aberrations. To relate this distribution to the location of the alpha-source, a

[7] S. Rosenblum and G. Dupouy, Compt. rend. **194**, 1919 (1932).
[8] J. W. M. DuMond, Phys. Rev. **77**, 411 (1950).
[9] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 250 (1934).
[10] G. H. Briggs, Proc. Roy. Soc. (London) **A157**, 183 (1936).
[11] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937), Eq. (770).

low power microscope was used with a 6× objective and a 10× ocular with scale. The source wire and a fiducial mark on the plate holder were swung in succession into the field of view, and measurements were made between the observed positions. This permitted an accuracy of at least 0.05 mm for each measurement, so that the possible error in Hr due to an uncertainty in our knowledge of this relative location is only 1 part in 10,000.

As discussed previously,[1-3] the sharpness of the high energy edge of the peak of tracks observed on the photographic plates determines the precision with which the peak can be located. In general, this sharpness is established by the statistics of the number of tracks collected in the peak and, for most of the results presented here, was such as to permit the location of the high energy edge to within 0.1 mm. The plates on which the peaks are detected are 2 inches long, and their mean distance from the target is 710 mm. Thus, the possible error in the measurement of particle energy due to this uncertainty in the location of the peak is 2 parts in 7000.

A circuit for stabilizing the current supply to the annular magnet has been used during most of the work reported here. This circuit does not supply the entire magnet current. It operates by bypassing a fraction of the current through a 6L6, the amount bypassed swinging from 0 to 0.2 amp in response to an error signal from a potentiometer and galvanometer system connected across a standard resistor in the magnet circuit. Deflection of the galvanometer from the normal balance position is detected by photo-cells in the galvanometer light beam. Except for a few minor changes, this circuit is the same as that used for maintaining constant current through the fluxmeter coil. With the stabilizing circuit in use, it is possible to employ in a routine fashion the full sensitivity, about 3 parts in 10^5, of the fluxmeter. Stability of the annular magnet is particularly important when making measurements on high energy particles where small changes in magnetic field represent large kev shifts.

The rectangular magnet, which is used to deflect the incident ion beam through 90 degrees and thus define its energy, has been operated without automatic stabilization. Fluctuations of this magnetic field contribute no more than about 5-kev uncertainty to the observations on reaction energies even in those reactions whose Q-values are most sensitive to changes in the incident energy.

The effects of surface contamination on the targets on the energies of the bombarding and emitted particles were given careful attention. They are of particular importance in low energy reactions and in those involving alpha-particle emission. We have used six different methods of estimating these effects:

1. A given reaction may be observed by means of the recoil nuclei as well as of the lighter emitted particle. The $Be^9(d, \alpha)Li^7$ reaction is a good illustration. This reaction leads to the emission from the target of energetic Li^7 particles which are singly, doubly, and triply charged. Since the doubly charged particles are focused at nearly the same field strength as the alpha-particles, they are the most convenient to study. In the absence of surface contamination, the Q-value obtained for $Be^9(d, \alpha)Li^7$ should be the same as that for $Be^9(d, Li^{7++})He^4$. However, if there is contamination present, it will affect the emitted alpha less than it does the Li^{7++}, thereby leading to a lower value for the reaction energy observed by the latter reaction. By comparing the losses of energy per unit thickness of contamination for the incident deuteron, the emitted alpha, and the Li^{7++}, it is possible to express the shift of the Q for $Be^9(d, \alpha)Li^7$ from its true value in terms of the difference between the observed Q's for $Be^9(d, \alpha)Li^7$ and $Be^9(d, Li^{7++})He^4$. Another example of this method is $Li^6(p, \alpha)He^3$ and $Li^6(p, He^{3++})He^4$.

Where suitable, this method provides a very convincing demonstration of the amount of surface contamination. Unfortunately, it is useful in only a very limited number of reactions, since in only a few do the recoil nuclei have sufficient energy to make observable tracks in the emulsion.

2. Method 1 can be extended for use where its direct application is not possible. For instance, in the $Be^9(d, p)Be^{10}$ and $Be^9(p, d)Be^8$ reactions, it is not possible to observe the recoil nuclei. However, using the example of Method 1, the air equivalence of the contamination over the Be^9 target can be calculated and then used to correct the measurements of other reaction energies using this target.

3. Where neither Method 1 nor 2 is suitable, shifting the incident energy over wide limits will achieve somewhat the same effect, since the energy losses for both the incident and the emitted particles will be different at the different voltages. However, this is not so sensitive a method as is 1.

4. In the case of targets evaporated onto thin foil backings, it is possible to examine the elastic scattering of the incident ions by both the target material and surface contamination. Any difference between the energies of the ions scattered by the target material nda of those scattered by the surface contamination, other than the difference predicted by conservation of momentum, is attributable to the thickness of the contamination and may be used to calculate this thickness. With a target evaporated onto a thin Formvar foil, the ions scattered by carbon and by oxygen show double peaks, the high energy ones being due to surface contamination on the target material, whereas, the others are due to the carbon and to the oxygen in the Formvar foil.

5. The target may be deliberately heated prior to and during bombardment in order to drive off volatile contaminants. However, the difficulty is frequently encountered of evaporating away the target material itself ,when using temperatures sufficiently high to ensure freedom from contamination.

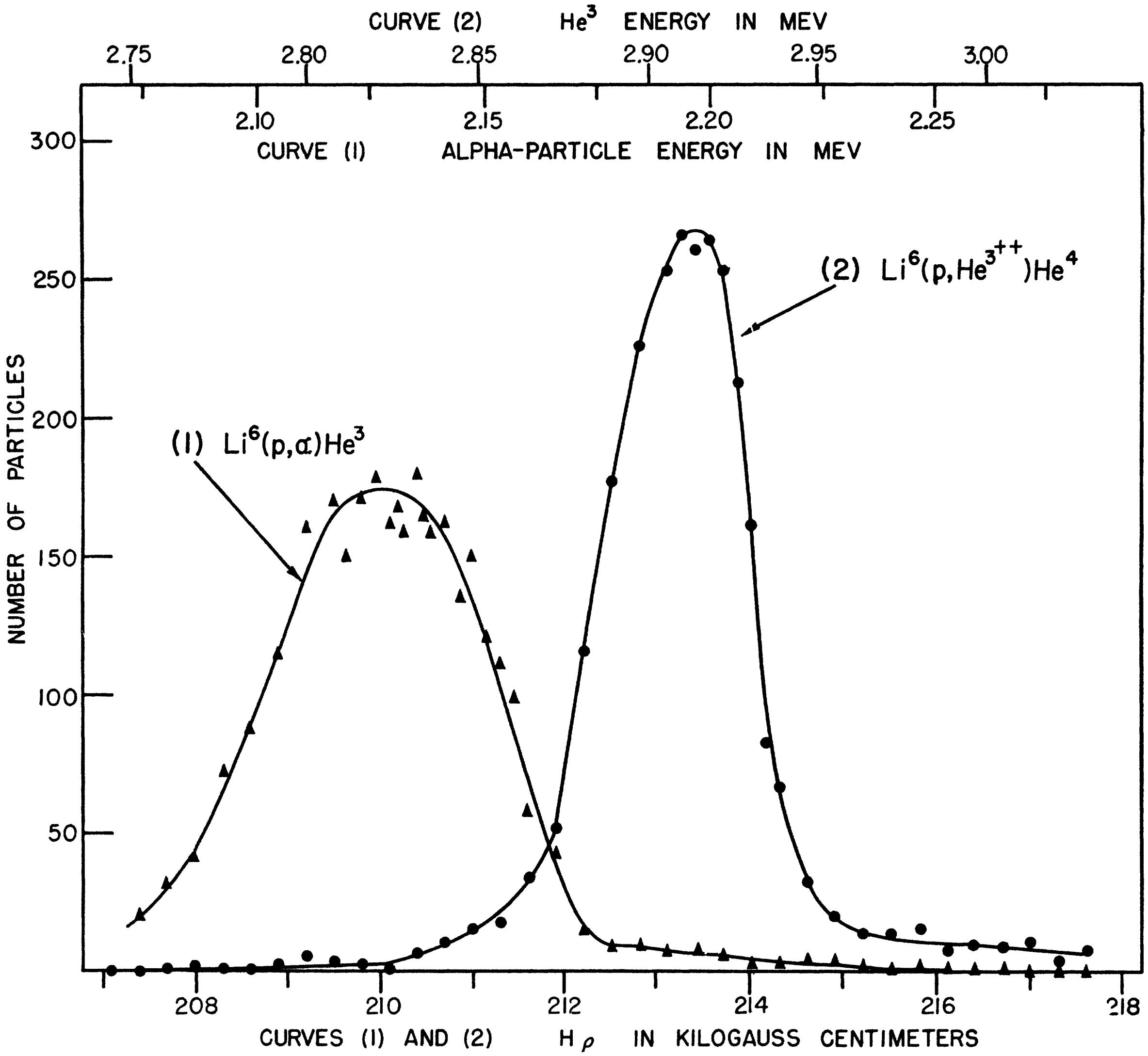

FIG. 1. Alpha-particle and He^{3++} groups from Li^6SO_4 target bombarded by 1.51-Mev protons.

6. If none of the above methods is suitable, it is necessary to rely on the use of freshly prepared targets. Experience has shown that the contamination builds up during prolonged bombardment. Therefore, if it is not possible to correct for the contamination by one of the above methods, it becomes necessary to prepare a fresh target for each bombardment. If several independently prepared targets lead to consistent values for the reaction energy, it is reasonable to assume that there is but little contamination.

III. RESULTS

A series of measurements has been made of the reaction energies of thirty-eight ground-state transitions induced by proton and deuteron bombardment of light elements from deuterium through sulfur. The bombarding energy used was usually close to 1.5 Mev; however, in a few cases, bombarding energies from 0.7 to 1.8 Mev were used. In the following sections, the reactions investigated for each nucleus are described. Each of the Q-values reported has been derived from a relativistic Q-equation, and the stated uncertainty has been arrived at from a consideration of the effect on the particular reaction of the various possible sources of error mentioned in Sec. II and in reference 4.

$D^2(d, p)T^3$

It is difficult to prepare thin deuterium targets directly, but this reaction may be observed from the deuterium deposited on targets exposed to the beam. A sharp proton group which we ascribe to this source has been found from a target of SiO_2 evaporated onto platinum sheet. Measurements on the energy of this group were made at bombarding energies of 1.60, 1.70, and 1.81 Mev. The Q-values obtained for these three energies agree to within ± 3 kev, the average being

4.030±0.006 Mev. The group was identified as arising from deuterium, since a change of 105±3 kev in the bombarding energy produced a change of 25.8±1.8 kev in the energy of the group. This is in accord with the change of 26.1±0.8 kev expected from the $D^2(d, p)T^3$ reaction and could not be correlated with the energy shift expected from any other (d, p) reaction. For example, for a target nucleus of mass 3, the shift would be 52±2 kev. This value of 4.030±0.006 Mev is in good agreement with a previous value of 4.036±0.022 Mev also obtained from magnetic analysis.[12] As will be mentioned in a later section, it is also in agreement with the value calculated from the Q-values measured for the $C^{12}(d, p)C^{13}$ and $C^{13}(d, t)C^{12}$ reactions.

$Li^6(p, \alpha)He^3$

The target used for this reaction was a thin layer of lithium sulfate, enriched in the Li^6 isotope evaporated onto a platinum backing. (The enriched lithium was obtained from the Isotopes Division, AEC, Oak Ridge.) It was found possible to observe on the same nuclear-track plate both the He^{3++} and alpha-particle groups emitted from Li^6 when bombarded by protons, as shown in Fig. 1. The ranges of the He^{3++} and He^4 particles in the nuclear-track emulsions were sufficiently different to permit the accurate resolution of the two groups. In addition, an estimate of surface contamination present could be made from the simultaneous observation of these two groups. The effect of surface contamination would be to make the Q-value determined from the He^4 group lower than that of the He^3 group because of the higher loss of energy of the alpha-particles for a given layer of contaminant. The observed Q-values for the $Li^6(p, \alpha)He^3$ and $Li^6(p, He^{3++})He^4$ reactions were 4.0202 and 4.0185 Mev, respectively. The difference between these values is −1.7±5.1 kev, indicating a correction for surface contamination of less than 3.4 kev for the $Li^6(p, \alpha)He^3$ reaction. The resulting Q-value for the $Li^6(p, \alpha)He^3$ reaction is 4.021±0.006 Mev, in agreement with the values of 4.017±0.022 Mev[13] and 3.97±0.03 Mev[14] found by other workers using magnetic analysis.

$Li^6(d, p)Li^7$

Immediately following the observation of the $Li^6(p, \alpha)He^3$ reaction, deuterons were substituted for protons as bombarding particles, and the $Li^6(d, p)Li^7$ ground-state proton group was observed. The correction for contamination was negligible for this reaction, being less than 0.1 kev. From an average of two independent observations, the Q-value of this reaction was measured as 5.019±0.007 Mev. This value is somewhat higher than the earlier value of 5.006±0.014 Mev[2] reported by this laboratory. In this earlier work, no correction was made for surface contamination. The only previous measurement of this reaction energy was $Q=5.02 \pm 0.12$ Mev[15] from range measurements.

$Li^7(p, \alpha)\alpha$

The $Li^7(p, \alpha)\alpha$ alpha-particle group was observed from the same lithium-sulfate target (enriched in Li^6) that was used for the investigation of the $Li^6(p, \alpha)He^3$ reaction described in the previous section. Since the alpha-particles from this reaction have high energy (9 Mev), the correction for surface contamination was negligible (less than 1 kev). As has been reported,[16] the Q-value measured for the $Li^7(p, \alpha)\alpha$ reaction was 17.340±0.014 Mev, which is considerably higher than the earlier range measurement of 17.28±0.03 Mev.[17] However, our value has been recently confirmed by Whaling and Li,[18] who find a value of 17.338±0.011 Mev from magnetic analysis and direct comparison with ThC′ alpha-particles.

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

Our earlier measurement of the $Li^7(d, p)Li^8$ reaction was made using a thin target of LiF on a silver backing, and the resulting Q-value of −0.193±0.008 Mev reported.[2] However, an observation of the $Li^7(p, \alpha)\alpha$ alpha-group was also made at that time which gave a Q-value of 17.338. Comparison with the later value of 17.340 Mev for the $Li^7(p, \alpha)\alpha$ reaction results in a correction of 5.5±5.5 kev due to surface contamination for the Q-value of the $Li^7(d, p)Li^8$ reaction. The revised Q-value of this reaction is −0.188±0.007 Mev. These results have been recently confirmed by Paul,[19] who reports a Q-value of −0.187±0.010 Mev from the measurement of the angle of recoil of the Li^8 nuclei.

$Li^7(d, \alpha)He^5$

An investigation of the $Li^7(d, \alpha)He^5$ reaction was made at 1.51-Mev bombarding energy using a thin target of LiOH evaporated onto a platinum backing. In contrast to the observations of all other ground-state transitions studied to date at this laboratory, no sharp ground-state group was found. Instead, a continuous distribution of alpha-particles was observed.

From a maximum energy of about 9 Mev, the number of alpha-particles in the distribution increased to a broad maximum at about 8.3-Mev alpha-particle energy, then decreased slowly at lower alpha-energies. The midpoint of the increasing slope occurred in a region of 8.45- to 8.63-Mev alpha-energy, corresponding to an energy release of 14.3 to 14.6 Mev. These observations are somewhat in contrast to the range measurements of

[12] Tollestrup, Jenkins, Fowler, and Lauritsen, Phys. Rev. **75**, 1947 (1949).
[13] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).
[14] W. E. Burcham and J. M. Freeman, Phil. Mag. **41**, 921 (1940).
[15] J. D. Cockcroft and E. T. Walton, Proc. Roy. Soc. (London) **A144**, 704 (1934).
[16] Strait, Van Patter, Sperduto, and Buechner, Phys. Rev. **81**, 315 (1951).
[17] N. R. Smith, Phys. Rev. **56**, 548 (1939)
[18] W. Whaling and C. W. Li (private communication).
[19] E. B. Paul, Phil. Mag. **41**, 942 (1950).

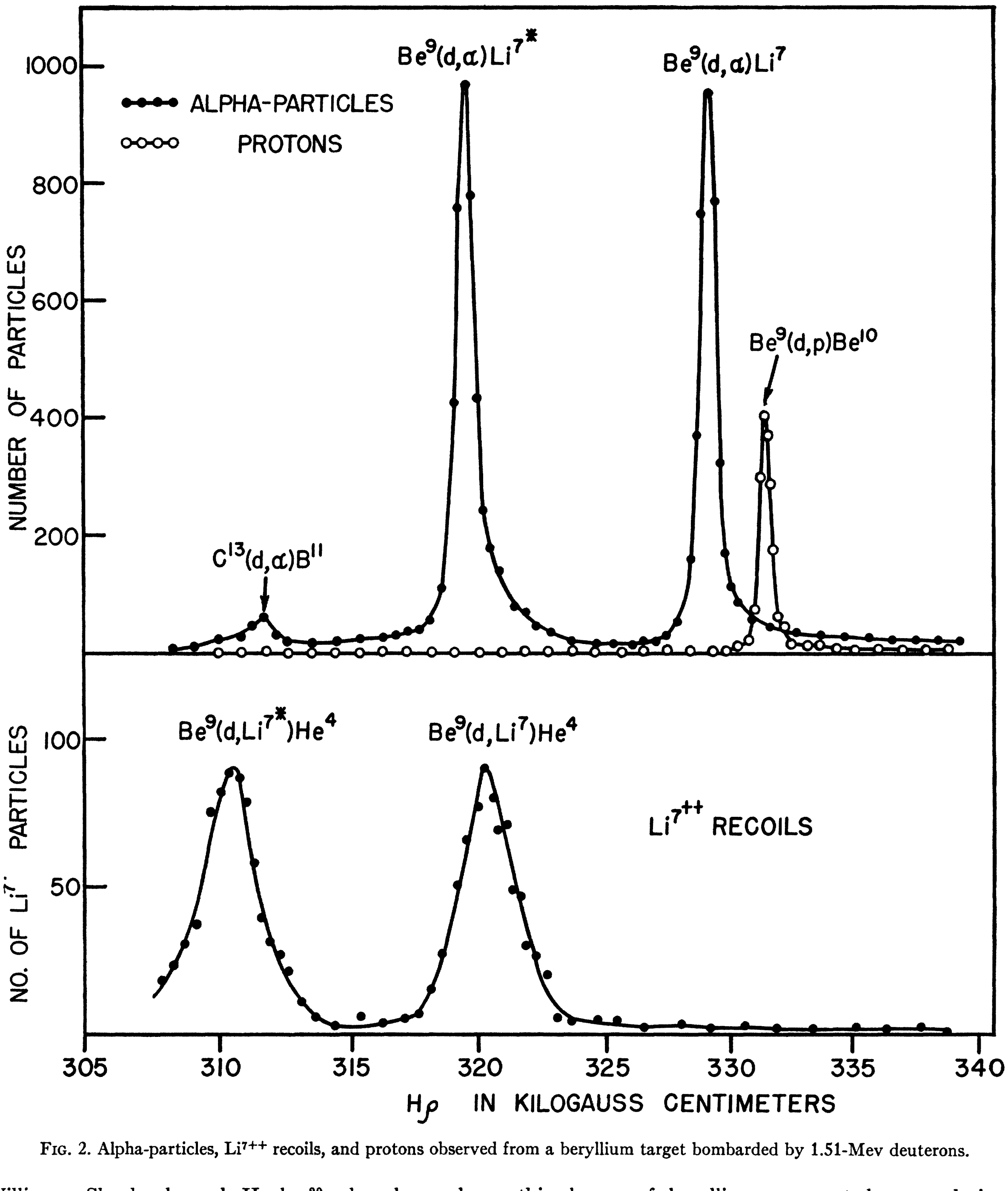

FIG. 2. Alpha-particles, Li^{7++} recoils, and protons observed from a beryllium target bombarded by 1.51-Mev deuterons.

Williams, Shepherd, and Haxby,[20] who observed a $Li^7(d, \alpha)He^5$ alpha-group with a Q of 14.3 Mev and a half-width of 0.14 Mev at 0.2-Mev bombarding energy.

Be^9

Accurate determinations have been made of the reaction energies of the (p, d), (p, α), (d, α), and (d, p) reactions of the nucleus Be^9. The targets used consisted of thin layers of beryllium evaporated onto platinum backings.

[20] Williams, Shepherd, and Haxby, Phys. Rev. **51**, 888 (1937).

$Be^9(p, d)Be^8$

A study was made of the reaction $Be^9(p, d)Be^8$ at two bombarding energies which differed by 0.75 Mev. Because of the low Q-value of this reaction, the result of such a change in bombarding energy provides a fairly good method of estimating the amount of surface contamination present, since any surface layers would cause the Q-value observed at the lower bombarding energy to be lower also. The Q-value observed at 0.75- and 1.5-Mev bombarding energies were 0.565 ± 0.004 Mev and 0.560 ± 0.006 Mev, indicating that the correction for contamination was negligible within the error of determination of ±4 kev. The weighted average of three measurements is $Q=0.562\pm0.004$ Mev, in good agreement with the reported value of 0.558 ± 0.003 Mev[13] and in fair agreement with other previously reported values of 0.547 ± 0.006 Mev[21] and 0.541 ± 0.003 Mev.[22] The present value is also in excellent agreement with the figure of 0.560 ± 0.004 Mev obtained from the recent precise measurements of the photo-neutron thresholds of beryllium and deuterium.[23]

$Be^9(d, \alpha)Li^7$

As described in an earlier section, the Q-value of the $Be^9(d, \alpha)Li^7$ ground-state reaction can be corrected for surface contamination by observation of both the alpha-particles and the Li^{7++} recoils. As illustrated by the data in Fig. 2, an observation was made of the Li^7 recoils corresponding to the ground-state reaction and of the alpha-particle group corresponding to the 478.5-kev[24] excited state of Li^7. The measured Q-values of these groups were 7.1399 and 6.6687 Mev. A Q-value of 7.1472 Mev was thus indicated for the $Be^9(d, \alpha)Li^7$ ground-state alpha-group. Hence, the observed difference in Q-values obtained from the alpha-particles and Li^{7++} recoils was 7.3 ± 3.4 kev. After correction for the contribution to the half-width due to geometry, the ratio of the energy losses per unit thickness of surface layer was estimated from the observed half-widths of the Li^{7++} and alpha-particle groups. From the difference in observed Q-values, a correction for contamination of 1.5 ± 0.7 kev was calculated for the $Be^9(d, \alpha)Li^7$ Q-value. As a result of two such measurements, an average Q-value for the $Be^9(d, \alpha)Li^7$ ground-state reaction was found to be 7.150 ± 0.008 Mev. This is slightly higher than the earlier value of 7.145 ± 0.024 Mev reported[3] from our laboratory. This earlier value was not corrected for surface contamination. Recently, Whaling and Li[18] have measured a Q-value of 7.151 ± 0.010 Mev using magnetic analysis. This is in excellent agreement with the value reported here.

$Be^9(p, \alpha)Li^6$

Immediately following the measurement of the Li^{7++} and alpha-particle groups from the $Be^9(d, \alpha)Li^7$ reaction, the $Be^9(p, \alpha)Li^6$ ground-state alpha-group was observed from the same beryllium target. Assuming that the amount of surface contamination had not changed, a correction for contamination of 2.7 ± 1.3 kev was estimated for the $Be^9(p, \alpha)Li^6$ reaction. The Q-value found is 2.142 ± 0.006 Mev, somewhat higher than the previously reported value of 2.121 ± 0.012 Mev, also obtained from magnetic analysis by Tollestrup, Fowler, and Lauritsen.[13]

$Be^9(d, p)Be^{10}$

An earlier measurement was made of the $Be^9(d, \alpha)Li^7$ reaction using a target with a considerably larger amount of surface contamination. On the same nuclear-track plate, the $Be^9(d, p)Be^{10}$ ground-state proton group was observed, as indicated in Fig. 2. The correction for surface contamination was estimated to be 1.9 ± 0.2 kev for the $Be^9(d, p)Be^{10}$ reaction, resulting in a corrected Q-value of 4.585 ± 0.008 Mev. This value is somewhat higher than our earlier reported[3] value of 4.576 ± 0.012 Mev, which was not corrected for surface contamination. An accurate check on our value is provided by the recent measurement with a pair spectrometer of the $Be^9(n, \gamma)Be^{10}$ Q-value. This has been reported by Kinsey *et al.*[25] as 6.797 ± 0.008 Mev. Combining their result with the latest value of 2.226 ± 0.003 Mev[23] for the deuteron binding energy, a Q-value of 4.571 ± 0.009 Mev is calculated for the $Be^9(d, p)Be^{10}$ reaction. Although this is somewhat lower than our value of 4.585 ± 0.008 Mev, the difference is within the errors of the measurement.

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

The $B^{10}(p, \alpha)Be^7$ ground-state alpha-particles were first observed from a thin target of boron evaporated onto a thin film of Formvar. The B^{10} content of the boron used was enriched to 96 percent. (The enriched boron was obtained from the Isotopes Division, AEC, Oak Ridge.) This target had been exposed to long beam bombardments. The measured Q-value was 1.134 Mev. However, the incident proton energy calculated from the observed $B^{10}(p, p)B^{10}$ group was 3 kev lower than that calculated from the $C^{12}(p, p)C^{12}$ group, indicating a surface layer of carbon which would lower the $B^{10}(p, \alpha)Be^7$ Q-value by about 20 kev. Fresh targets of enriched B^{10} were evaporated onto platinum backings, and the $B^{10}(p, \alpha)Be^7$ ground-state group was observed at 1.30-Mev bombarding energy. The average Q-value from two measurements from targets not previously bombarded is 1.152 ± 0.004 Mev, verifying the earlier rough estimate of surface contamination. This value for the $B^{10}(p, \alpha)Be^7$ reaction has already been reported[6] and is in agreement with the values of 1.148 ± 0.006 Mev[26] and 1.147 ± 0.010 Mev[27] reported by other workers.

$B^{10}(d, p)B^{11}$

The ground-state proton group from the $B^{10}(d, p)B^{11}$ reaction has been observed from targets of enriched B^{10}

[21] Allison, Skaggs, and Smith, Phys. Rev. **57**, 550 (1940).
[22] L. del Rosario, Phys. Rev. **74**, 304 (1948).
[23] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).
[24] Ter-Pogossian, Robinson, and Goddard, Phys. Rev. **76**, 1407 (1949).
[25] Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
[26] Brown, Chao, Fowler, and Lauritsen, Phys. Rev. **78**, 88 (1950)
[27] W. E. Burcham and J. M. Freeman, Phil. Mag. **41**, 337 (1950).

and natural boron on platinum and thin Formvar backings. The average of seven independent observations gave a Q-value of 9.235±0.011 Mev. A preliminary report of this result has already been given.[28]

$B^{11}(p, \alpha)Be^8$

Three measurements were made of the Q-value of the $B^{11}(p, \alpha)Be^8$ ground-state alpha-group using thin targets of natural boron which had not been previously bombarded. The three Q-values obtained agreed within ±1 kev, indicating the absence of appreciable contamination and giving an average value of 8.567±0.011 Mev. The only previous value reported is 8.60±0.10 Mev from range measurements.[29]

$B^{11}(d, p)B^{12}$

The results for the $B^{11}(d, p)B^{12}$ reaction have been previously described in detail.[5] Three observations were made of the ground-state proton group at deuteron bombarding energies of 0.7, 1.51, and 1.67 Mev. The Q-values obtained from these measurements agreed within 2 kev, indicating that no correction was necessary for surface contamination. The average Q-value obtained for the $B^{11}(d, p)B^{12}$ reaction was 1.136±0.005 Mev.

$B^{11}(d, \alpha)Be^9$

Three determinations of the $B^{11}(d, \alpha)Be^9$ ground-state Q-value were made from targets that had not been previously bombarded. As has been reported,[30] the resulting values agreed within ±3 kev, giving an average value of 8.018±0.007 Mev.

$C^{12}(d, p)C^{13}$

A careful remeasurement of the $C^{12}(d, p)C^{13}$ reaction energy has been made from several observations of the ground-state proton group originating from surface contamination containing carbon that occurs on all targets. Seven determinations of the $C^{12}(d, p)C^{13}$ reaction energy were made, all of which agreed within ±4 kev. The weighted average of these values is 2.716±0.005 Mev, somewhat lower than the earlier value of 2.729 ±0.009 Mev previously reported[4] from this laboratory. Two independent confirmations of this value can be obtained from results on other reactions. From the $C^{12}(d, n)N^{13}$ and $C^{13}(p, n)N^{13}$ Q-values of −0.281±0.003 Mev[31] and −3.003±0.003 Mev,[32] a Q-value of 2.722 ±0.004 Mev for the $C^{12}(d, p)C^{13}$ reaction may be calculated. A combination of the $C^{12}(n, \gamma)C^{13}$ Q-value of 4.947±0.008 Mev[33] and the deuteron binding energy of 2.226±0.003 gives a $C^{12}(d, p)C^{13}$ Q-value of 2.720±0.009 Mev. These values are in good agreement with the present result.

$C^{13}(d, t)C^{12}$

There have been no previous reports concerning the $C^{13}(d, t)C^{12}$ reaction. However, in these investigations, a group of particles was observed whose range in the nuclear-track plates was slightly less than the range for alpha-particles giving the same Hr value, indicating that the particles could be identified as tritons. For a change in bombarding energy of 188±3 kev, the observed energy change of this group was 126±3 kev compared with an expected change of 125±2 kev for a triton group from the $C^{13}(d, t)C^{12}$ reaction. The change in Hr was much greater than could be expected for a (d, p) or a (d, α) group reaction. This triton group was observed from four different targets, evidently originating from the 1.1 percent of C^{13} in the natural carbon contamination on the targets. The weighted average of five determinations, agreeing within ±2 kev, gave a Q-value of 1.310±0.006 Mev for the $C^{13}(d, t)C^{12}$ reaction.‡ Combining this result with our measurement of the $C^{12}(d, p)C^{13}$ reaction Q-value, a Q-value of 4.026±0.008 Mev is calculated for the $D^2(d, p)T^3$ reaction. This result agrees within the experimental errors with the directly measured value of 4.030±0.006 Mev previously mentioned.

$C^{13}(d, p)C^{14}$ and $C^{13}(d, \alpha)B^{11}$

Investigations of the $C^{13}(d, p)C^{14}$ and $C^{13}(d, \alpha)B^{11}$ ground-state reactions were made using targets of $BaCO_3$ in which the C^{13} content was enriched to 52 percent. (The enriched carbon was obtained from The Eastman Kodak Company.) In addition, both ground-state groups have been observed from the natural carbon contamination (1.1 percent C^{13}) on various targets.

The $C^{13}(d, p)C^{14}$ and $C^{13}(d, \alpha)B^{11}$ ground-state Q-values were determined to be 5.948±0.008 Mev[34] and 5.160±0.010 Mev from a weighted average of at least three measurements in both cases. The fact that the Q-values for groups arising from surface carbon contamination agreed within 5 kev with these values indicated that the correction for surface contamination could be considered as negligible.

$N^{14}(d, p)N^{15}$ and $N^{14}(d, \alpha)C^{12}$

The $N^{14}(d, p)N^{15}$ and $N^{14}(d, \alpha)C^{12}$ reactions were investigated at 1.42-Mev bombarding energy using a tantalum-nitride target on a platinum backing. This target was heated to a dull red color during exposures in order to drive off volatile contaminants. Since hot

[28] D. M. Van Patter and W. W. Buechner, Phys. Rev. **79**, 240 (1950).
[29] Oliphant, Kempton, and Rutherford, Proc. Roy. Soc. (London) **A150**, 241 (1935).
[30] Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. **81**, 233 (1951).
[31] Bonner, Evans, and Hill, Phys. Rev. **75**, 1398 (1949).
[32] H. T. Richards and R. V. Smith, Phys. Rev. **77**, 752 (1950).
[33] Kinsey, Bartholomew, and Walker, Phys. Rev. **77**, 723 (1950).

‡ We are indebted to R. G. Thomas for his suggestion that this triton group might be observed in our experiments.
[34] Sperduto, Holland, Van Patter, and Buechner, Phys. Rev. **80**, 769 (1950).

tantalum combines readily with both nitrogen and oxygen, there was a possibility that nonvolatile surface contaminants remained even at high temperatures. The existence of such contaminants was investigated by a comparison of the Q-values obtained for a $N^{14}(d, \alpha)C^{12*}$ alpha-particle group from the heated tantalum-nitride target and from a freshly prepared target consisting of a thin layer of ammonium nitrate deposited on a platinum backing. It was found that a small amount of such contamination was indeed present, and the measured $N^{14}(d, p)N^{15}$ and $N^{14}(d, \alpha)C^{12}$ Q-values obtained with the tantalum-nitride target were corrected accordingly.

As has been reported,[35] the Q-value obtained for the $N^{14}(d, p)N^{15}$ ground-state reaction is 8.615 ± 0.009 Mev. The fact that the Q-values of the ground-state proton group from nitrogen contamination on other targets agreed with this value within ±5 kev indicated that the correction for contamination for this Q-value was negligible. The recent measurement of the $N^{14}(n, \gamma)N^{15}$ Q-value as 10.823 ± 0.012 Mev[33] provides an accurate comparison with our results. After subtraction of the deuteron binding energy from the $N^{14}(n, \gamma)N^{15}$ Q-value, a Q-value of 8.597 ± 0.014 Mev is predicted for the $N^{14}(d, p)N^{15}$ reaction, in agreement with our result within the stated errors.

For reasons that will be described in a succeeding section, the Q-value obtained from measurements made on the $N^{14}(d, \alpha)C^{12}$ ground-state alpha-group was not considered so reliable as the value predicted from a combination of other reaction energies determined in this work.

N^{15}

The (d, α), (p, α), and (d, p) reactions of N^{15} were investigated using tantalum-nitride targets in which the nitrogen content was enriched to 60 percent N^{15}. (The enriched nitrogen was obtained in the form of NH_4NO_3 from the Eastman Kodak Company.) Comparison with the results obtained from tantalum-nitride targets of normal nitrogen (0.4 percent N^{15}) permitted the identification of the groups arising from the N^{15} isotope.

$N^{15}(d, \alpha)C^{13}$

The $N^{15}(d, \alpha)C^{13}$ ground-state group was observed at 1.42-Mev bombarding energy from a heated tantalum-nitride target. A correction for contamination of 6 ± 2 kev was estimated from the comparison of the Q-values for a $N^{14}(d, \alpha)C^{12}$ group from this target and an ammonium-nitrate target not previously bombarded. The corrected Q-value for the $N^{15}(d, \alpha)C^{13}$ reaction was 7.681 ± 0.009 Mev, compared with the only previously reported value of 7.54 ± 0.07 Mev,[36] which was obtained from range measurements.

[35] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[36] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

$N^{15}(p, \alpha)C^{12}$

The $N^{15}(p, \alpha)C^{12}$ ground-state proton group was observed at 1.20-Mev bombarding energy, corresponding to a resonance for the yield of this group.[37] The heated target used was the same as for the $N^{15}(d, \alpha)C^{13}$ reaction; assuming the same amount of surface contamination, the correction for contamination was estimated as 7 ± 3 kev. The Q-value found for the $N^{15}(p, \alpha)C^{12}$ reaction is 4.960 ± 0.007 Mev, which is in agreement with a recently reported value of 4.96 ± 0.05 Mev[38] from magnetic analysis.

$N^{15}(d, p)N^{16}$

A search was made for the ground-state group of the $N^{15}(d, p)N^{16}$ reaction at 1.42-Mev bombarding energy. Only one proton group was found that could be assigned to the N^{15} isotope; this group had a Q-value of -0.034 ±0.005 Mev.[35] The only previous investigation of the $N^{15}(d, p)N^{16}$ reaction was recently reported by Wyly,[39] who used targets of normal and enriched ammonia (61 percent N^{15}). By subtracting the normal-target data from the enriched-target data, he obtained a proton group that was assigned to the ground-state reaction of $N^{15}(d, p)N^{16}$. This was closely accompanied by a more intense group that was assigned to an excited state in N^{16} at about 0.3-Mev excitation. The Q for the higher energy group was 0.23 ± 0.15 Mev. It is possible that our observed $N^{15}(d, p)N^{16}$ proton group corresponds to the more intense group reported by Wyly and does not correspond to the ground-state transition.

$O^{16}(d, p)O^{17}$ and $O^{16}(d, \alpha)N^{14}$

Precise determinations have been made of the $O^{16}(d, p)O^{17}$ and $O^{16}(d, \alpha)N^{14}$ reaction energies, using targets consisting of a thin layer of Formvar (containing oxygen) on platinum backings. Two measurements of the $O^{16}(d, p)O^{17}$ Q-value, agreeing within 1 kev, gave an average value of 1.917 ± 0.008 Mev, which is somewhat lower than the value of 1.925 ± 0.005 Mev[4] previously reported. From two independent determinations agreeing within 1 kev, the Q-value of the $O^{16}(d, \alpha)N^{14}$ ground-state reaction was measured as 3.112 ± 0.006 Mev, as has been reported.[16] The correction for surface contamination is considered to be negligible for both these determinations. No measurements of comparable precision have been reported in the literature for these reactions.

F^{19}

Investigations of the (p, α), (d, p), and (d, α) reactions of F^{19} have been made. The ground-state groups from these reactions were first observed from targets of CaF_2, MgF_2, and LiF evaporated onto silver backings.

[37] Schardt, Fowler, and Lauritsen, Phys. Rev. **80**, 136 (1950).
[38] J. M. Freeman, Proc. Roy. Soc. (London) **63A**, 668 (1950).
[39] L. D. Wyly, Phys. Rev. **76**, 316 (1949).

All of these targets had been exposed to long beam bombardments, and it was found that large surface layers of contamination were present on them. As a result, fresh targets of PbF_2 evaporated onto platinum backings were prepared, and the ground-state groups were re-examined.

$F^{19}(p, \alpha)O^{16}$

The reaction energy of the $F^{19}(p, \alpha)O^{16}$ reaction was initially reported at 8.068 Mev.[40] However, this Q-value was measured again using a PbF_2 target not previously bombarded and was found to be 8.118±0.009 Mev. This result is in agreement with the value of 8.113±0.030 Mev reported by Chao *et al.*[41] from a combination of measured Q-values for the low energy alpha-particles from $F^{19}(p, \alpha)O^{16*}$ and gamma-ray measurements on the same reaction. Freeman[38] has recently reported a somewhat lower Q-value of 8.06±0.04 Mev, using magnetic analysis.

$F^{19}(d, \alpha)O^{17}$ and $F^{19}(d, p)F^{20}$

The ground-state Q-values of the $F^{19}(d, \alpha)O^{17}$ and $F^{19}(d, p)F^{20}$ reactions have been measured as 10.050 ±0.010 and 4.373±0.007 Mev from PbF_2 targets not previously bombarded. The $F^{19}(n, \gamma)F^{20}$ reaction energy has been recently reported as 6.63±0.03 Mev,[25] corresponding to a Q-value of 4.40±0.03 Mev for the $F^{19}(d, p)F^{20}$ reaction, in agreement with the value determined in the present experiments within the stated errors.

$Na^{23}(d, p)Na^{24}$ and $Na^{23}(d, \alpha)Ne^{21}$

The $Na^{23}(d, p)Na^{24}$ and $Na^{23}(d, \alpha)Ne^{21}$ reactions have been investigated using targets of sodium hydroxide and sodium iodide evaporated onto platinum backings. Three independent measurements of the $Na^{23}(d, p)Na^{24}$ ground-state group gave Q-values which agree within ±3 kev, the weighted average being 4.731±0.009 Mev. Three measurements of the $Na^{23}(d, \alpha)Ne^{21}$ Q-value agreed within ±6 kev, the weighted average for this reaction being 6.902±0.010 Mev. The effect of surface contamination is assumed to be negligible for these determinations. In the earlier range measurements[42,43] on the $Na^{23}(d, \alpha)Ne^{21}$ reaction the alpha-particle groups corresponding to the ground state and 0.34-Mev excited state of Ne^{21} were not resolved. Reported Q-values for the $Na^{23}(p, \alpha)Ne^{20}$ and $Ne^{20}(d, p)Ne^{21}$ reactions of 2.35±0.04 Mev[38] and 4.50±0.09 Mev[44] give a predicted Q-value of 6.85±0.10 Mev for the $Na^{23}(d, \alpha)Ne^{21}$ reaction, which is in agreement with the result reported here.

$Mg^{24}(d, p)Mg^{25}$

Two observations were made of the $Mg^{24}(d, p)Mg^{25}$ ground-state proton group from a thin target of MgF_2 evaporated onto a platinum backing. The amount of surface contamination was estimated from a comparison of the Q-values of $F^{19}(d, p)F^{20}$ proton groups observed from this target with those found from fresh PbF_2 targets. The correction to the Q-value of the $Mg^{24}(d, p)Mg^{25}$ ground-state group due to surface contamination was found to be 3±3 kev. After allowance for this contamination, the Q-value was determined to be 5.094 ±0.010 Mev, which is somewhat higher than the value of 5.03±0.05 Mev[45] found from range measurements.

Al^{27}

The (d, p) and (d, α) ground-state reactions of Al^{27} have been investigated at bombarding energies from 1.2 to 2.0 Mev. Several targets were used, including thin layers of aluminum evaporated onto thin Formvar and platinum backings. In addition, a thin self-supporting foil of aluminum was used, which was obtained by dissolving away the Formvar backing of an evaporated aluminum target.

$Al^{27}(d, p)Al^{28}$

As has been reported,[46] the ground-state proton group previously observed in range measurements was found to be a doublet, corresponding to the ground state of Al^{28} and an excited state at 31±2 kev. The weighted average of five observations on the ground state, which agreed to within ±5 kev, gave a Q-value of 5.494±0.010 Mev. From a recent measurement of the $Al^{27}(n, \gamma)Al^{28}$ ground-state Q-value of 7.72±0.02 Mev,[25] a Q-value of 5.49±0.02 Mev may be calculated for the $Al^{27}(d, p)Al^{28}$ reaction, which is in excellent agreement with the present result.

$Al^{27}(d, \alpha)Mg^{25}$

A weighted average of five determinations of the $Al^{27}(d, \alpha)Mg^{25}$ reaction-energy group, which agreed to within ±5 kev, resulted in a Q-value of 6.694±0.010 Mev, as compared with a recent measurement of 6.62 ±0.05 Mev[47] obtained by magnetic analysis. However, combining the present Q-values for the $Al^{27}(d, \alpha)Mg^{25}$ and $Mg^{24}(d, p)Mg^{25}$ reactions, the $Al^{27}(p, \alpha)Mg^{24}$ reaction energy is calculated to be 1.600±0.014 Mev, which agrees with the recent accurate measurement of 1.585±0.015 Mev.[38]

$Si^{28}(d, p)Si^{29}$

An investigation of the $Si^{28}(d, p)Si^{29}$ reaction has been made at bombarding energies from 1.5 to 1.8 Mev, using

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40 Strait, Van Patter, and Buechner, Phys. Rev. **78**, 337 (1950).
41 Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
42 E. O. Lawrence, Phys. Rev. **47**, 17 (1935).
43 E. B. M. Murrell and C. L. Smith, Proc. Roy. Soc. (London) **A173**, 410 (1939).
44 A. Zucker and W. W. Watson, Phys. Rev. **78**, 14 (1950).
45 H. R. Allan and C. R. Wilkinson, Proc. Roy. Soc. (London) **A194**, 131 (1948).
46 Enge, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 317 (1951).
47 A. P. French and P. B. Treacy, Proc. Phys. Soc. (London) **63A**, 665 (1950).

thin targets of normal SiO_2 evaporated onto platinum. The ground-state proton group has also been observed from silicon contamination on other targets, evidently arising from the silicon in the stopcock grease used in the vacuum system. Five independent determinations, agreeing within ±4 kev, give a weighted average of the $Si^{28}(d, p)Si^{29}$ reaction energy of 6.246±0.008 Mev,[48] which is in fair agreement with the recent measurement of 6.18±0.09 Mev using range measurements.[49]

$Si^{30}(d, \alpha)Al^{28}$

There have been no previous investigations of the $Si^{30}(d, \alpha)Al^{28}$ reaction reported in the literature. From a combination of the $Al^{27}(\alpha, p)Si^{30}$ and $Al^{27}(d, p)Al^{28}$ Q-values of 5.49±0.01 and 2.38±0.2 Mev,[50] a Q-value of 3.1±0.2 Mev can be estimated for the $Si^{30}(d, \alpha)Al^{28}$ reaction. Similarly, a Q-value of 2.9±0.2 Mev is found from a combination of the $Si^{28}(d, p)Si^{29}$, $Si^{29}(d, p)Si^{30}$, and $Al^{28}(\beta^-)Si^{28}$ reaction energies.

A search was made for the $Si^{30}(d, \alpha)Al^{28}$ ground-state alpha-group from a target of $Si^{30}O_2$, in which the Si^{30} was enriched to 64 percent of the silicon content. (The enriched silicon was obtained from the Isotopes Division, AEC, Oak Ridge.) The SiO_2 was evaporated onto a platinum backing. An alpha-group of low intensity was observed which did not appear from a target of normal SiO_2. However, the alpha-group was superimposed on an appreciable background caused by scattered deuterons from the platinum backing. To eliminate this background, a target of $Si^{30}O_2$ was evaporated onto a thin film of Formvar stiffened by a layer of evaporated copper. The same alpha-group was again observed with the background considerably reduced. Seven determinations, agreeing within ±7 kev, gave an average Q-value of 3.120±0.010 Mev for this alpha-group. Since the Q-value is in agreement with the $Si^{30}(d, \alpha)Al^{28}$ reaction energy calculated from other reactions, this group has been assigned to the ground-state transition.

$Si^{30}(d, p)Si^{31}$

From a combination of the $P^{31}(n, p)Si^{31}$, $P^{31}(d, \alpha)Si^{29}$, and $Si^{29}(d, p)Si^{30}$ Q-values of −0.94±0.13 Mev,[51] 8.170 ±0.020, and 8.36±0.10 Mev,[49] a ground-state Q-value of 4.12±0.17 Mev is calculated for the $Si^{30}(d, p)Si^{31}$ reaction. Motz and Humphreys, using normal silicon and enriched Si^{30} targets, have recently reported a Q-value of 4.33±0.15 Mev[49] from range measurements.

An investigation of the $Si^{30}(d, p)Si^{31}$ reaction has been made using normal SiO_2 (3 percent Si^{30}) and enriched SiO_2 (64 percent Si^{30}) targets evaporated onto platinum backings. At 1.80-Mev bombarding energy a proton group with a Q-value of 4.364±0.010 Mev was observed from both types of targets. The ratio of the observed yields of this group was approximately equal to the ratio of the amounts of Si^{30} in the two targets. No additional $Si^{30}(d, p)Si^{31}$ proton groups with an intensity greater than 0.15 the intensity of the group with $Q=4.367$ Mev were observed in the energy range which would correspond to Q-values from 4.25 to 4.95 Mev. As a result, this proton group has been assigned to the ground-state $Si^{30}(d, p)Si^{31}$ transition.

$P^{31}(d, \alpha)Si^{29}$

The previously unreported $P^{31}(d, \alpha)Si^{29}$ ground-state alpha-group was observed at 1.81-Mev bombarding energy, both from a 300-kev phosphorus target and from a 20-kev zinc-phosphate target. The Q-values observed from these targets agreed within 1 kev, the average being 8.170±0.020 Mev.[48] Because several $Si^{28}(d, p)$ proton groups were observed from these targets, indicating the presence of an unknown amount of surface contamination, a probable error of 20 kev has been placed on the $P^{31}(d, \alpha)Si^{29}$ Q-value.

$P^{31}(d, p)P^{32}$

A search was made for the ground-state $P^{31}(d, p)P^{32}$ proton group at 1.81-Mev bombarding energy using a thin zinc-phosphate target evaporated onto a platinum backing. The Q-value of the ground-state group has been reported as 5.9±0.3 Mev[52] from range measurements. The highest energy proton group observed that could be assigned to the $P^{31}(d, p)P^{32}$ reaction had a Q-value of 5.704±0.009 Mev, an average of four determinations which agreed to within ±5 kev. Although this Q-value is about 0.2 Mev lower than expected from masses, the masses of nuclei in this region of the periodic table are not known to much better than 0.2 Mev.[53] In addition, a combination of the Q-values of −0.931±0.008 Mev,§ −19.15[53] (no error given), and −12.35±0.2 Mev[54] for the $S^{32}(n, p)P^{32}$, $S^{32}(\gamma, d)P^{30}$, and $P^{31}(\gamma, n)P^{30}$ reactions gives a predicted value of 5.68±0.2 Mev for the $P^{31}(d, p)P^{32}$ reaction. Finally, Allen and Rall[55] have recently investigated the $P^{31}(d, p)P^{32}$ reaction and find a Q-value of 5.42±0.10 Mev for the ground-state group. This Q-value may be too low, since we have found a $P^{31}(d, p)P^{32}$ group with $Q=5.627\pm0.009$ Mev which would not have been resolved from the ground-state group by the range measurements of Allen and Rall. In the light of the above evidence, it is concluded that the proton group with $Q=5.704\pm0.009$ Mev corresponds to the $P^{31}(d, p)P^{32}$ ground-state transition.

$S^{32}(d, p)S^{33}$

The $S^{32}(d, p)S^{33}$ ground-state proton group has been observed at 1.81-Mev bombarding energy from a thin

[48] Endt, Van Patter, and Buechner, Phys. Rev. **81**, 317 (1951).
[49] H. T. Motz and R. F. Humphreys, Phys. Rev. **80**, 595 (1950).
[50] H. H. Landon, Phys. Rev. **78**, 338 (1950).
[51] Metzger, Alder, and Huber, Helv. Phys. Acta **21**, 278 (1948).
[52] E. Pollard, Phys. Rev. **59**, 1086 (1940).
[53] A. S. Penfold, Phys. Rev. **80**, 116 (1950).
§ This value is obtained from the 1.713±0.008-Mev end point for the P^{32} beta-ray spectrum and the $(n-p)$ difference of 782±2 kev.
[54] McElhinney, Hanson, Becker, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
[55] R. C. Allen and W. Rall, Phys. Rev. **81**, 60 (1951).

TABLE I. Observed reaction energies.

Reaction	Q-value (Mev)	Reaction	Q-value (Mev)
$D^2(d,p)T^3$	4.030 ± 0.006	$N^{14}(d,p)N^{15}$	8.615 ± 0.009
$Li^6(p,\alpha)He^3$	4.021 ± 0.006	$N^{15}(p,\alpha)C^{12}$	4.960 ± 0.007
$Li^6(d,p)Li^7$	5.019 ± 0.007	$N^{15}(d,\alpha)C^{13}$	7.681 ± 0.009
$Li^7(p,\alpha)\alpha$	17.340 ± 0.014	$O^{16}(d,\alpha)N^{14}$	3.112 ± 0.006
$Li^7(d,p)Li^8$	-0.188 ± 0.007	$O^{16}(d,p)O^{17}$	1.917 ± 0.005
$Be^9(p,\alpha)Li^6$	2.142 ± 0.006	$F^{19}(p,\alpha)O^{16}$	8.118 ± 0.009
$Be^9(p,d)Be^8$	0.562 ± 0.004	$F^{19}(d,\alpha)O^{17}$	10.050 ± 0.010
$Be^9(d,\alpha)Li^7$	7.150 ± 0.008	$F^{19}(d,p)F^{20}$	4.373 ± 0.007
$Be^9(d,t)Be^8$	4.597 ± 0.013	$Na^{23}(d,\alpha)Ne^{21}$	6.902 ± 0.010
$Be^9(d,p)Be^{10}$	4.585 ± 0.008	$Na^{23}(d,p)Na^{24}$	4.731 ± 0.009
$B^{10}(p,\alpha)Be^7$	1.152 ± 0.004	$Mg^{24}(d,p)Mg^{25}$	5.094 ± 0.010
$B^{10}(d,p)B^{11}$	9.235 ± 0.011	$Al^{27}(d,\alpha)Mg^{25}$	6.694 ± 0.010
$B^{11}(p,\alpha)Be^8$	8.567 ± 0.011	$Al^{27}(d,p)Al^{28}$	5.494 ± 0.010
$B^{11}(d,\alpha)Be^9$	8.018 ± 0.007	$Si^{28}(d,p)Si^{29}$	6.246 ± 0.008
$B^{11}(d,p)B^{12}$	1.136 ± 0.005	$Si^{30}(d,\alpha)Al^{28}$	3.120 ± 0.010
$C^{12}(d,p)C^{13}$	2.716 ± 0.005	$Si^{30}(d,p)Si^{31}$	4.364 ± 0.010
$C^{13}(d,\alpha)B^{11}$	5.160 ± 0.010	$P^{31}(d,\alpha)Si^{29}$	8.170 ± 0.020
$C^{13}(d,t)C^{12}$	1.310 ± 0.006	$P^{31}(d,p)P^{32}$	5.704 ± 0.009
$C^{13}(d,p)C^{14}$	5.948 ± 0.008	$S^{32}(d,p)S^{33}$	6.422 ± 0.011

target of iron sulfide evaporated onto a platinum backing and also from sulfur contamination of a zinc-phosphate target. Three measurements of the ground-state Q-value agreed within ± 2 kev, giving a weighted average of 6.422 ± 0.011 Mev. The correction for surface contamination is considered to be negligible because, in the case of one measurement, the iron-sulfide target had not been previously bombarded. An accurate verification of this result is provided by the recent measurement of the $S^{32}(n,\gamma)S^{33}$ Q-value as 8.66 ± 0.02 Mev,[25] which gives a predicted $S^{32}(d,p)S^{33}$ Q-value of 6.43 ± 0.02 Mev.

In Table I, we have listed the reaction energies that have been measured in these experiments. We have omitted from this table the results of measurements on the $N^{15}(d,p)N^{16}$ reaction where there is an uncertainty regarding the identification of the ground-state group. We have also omitted the results on the $Li^6(d,\alpha)\alpha$, $B^{10}(d,\alpha)Be^8$, and $N^{14}(d,\alpha)C^{12}$ reactions. As will be discussed in the following section, we believe our experimental results on these three reactions are somewhat too high and that more accurate values are obtained from calculations based on the Q-values in Table I.

IV. DISCUSSION

The measurements which are outlined in the preceding paragraphs and which have led to the reaction energies listed in Table I were made over a considerable period of time. It is possible to check their internal consistency and to determine whether any systematic variation in our standards had occurred during this period by calculating certain of the Q-values from the others and by comparing the values thus obtained with those directly observed. As has been mentioned, the Q-value for $D^2(d,p)T^3$ calculated from the results on $C^{12}(d,p)C^{13}$ and $C^{13}(d,t)C^{12}$ agrees within 4 kev with the directly measured value. Four other such calculations and comparisons are:

$Be^9(p,\alpha)Li^6$	2.142 ± 0.006	$B^{11}(d,\alpha)Be^9$	8.018 ± 0.007
$Li^6(d,p)Li^7$	5.019 ± 0.007	$Be^9(p,d)Be^8$	0.562 ± 0.004
$Be^9(d,\alpha)Li^7$	7.161 ± 0.009 (calc)	$B^{11}(p,\alpha)Be^8$	8.580 ± 0.011 (calc)
$Be^9(d,\alpha)Li^7$	7.150 ± 0.008 (obs)	$B^{11}(p,\alpha)Be^8$	8.567 ± 0.011 (obs)
$N^{15}(p,\alpha)C^{12}$	4.960 ± 0.007	$F^{19}(p,\alpha)O^{16}$	8.118 ± 0.009
$C^{12}(d,p)C^{13}$	2.716 ± 0.005	$O^{16}(d,p)O^{17}$	1.917 ± 0.005
$N^{15}(d,\alpha)C^{13}$	7.676 ± 0.009 (calc)	$F^{19}(d,\alpha)O^{17}$	10.035 ± 0.011 (calc)
$N^{15}(d,\alpha)C^{13}$	7.681 ± 0.009 (obs)	$F^{19}(d,\alpha)O^{17}$	10.050 ± 0.010 (obs)

It can be seen that the four reaction cycles are consistent to within 5 to 15 kev and that, in all cases, the differences are within the stated uncertainties of the measurements. It is to be noted that in each case the observed value is compared with one calculated from two lower energy Q-values. Since in two of the cases the observed value is less than the one calculated, while in the other two cases it is higher, it is concluded that there is no systematic deviation in the measurements at the highest magnetic field strengths required to observe the reaction products from those reactions listed in Table I. This view is strengthened by the fact that for those reactions where measurements of comparable precision have been made by other workers their results are in general agreement with those in Table I.

In obtaining the results discussed above, the highest energy particles encountered were the protons from $B^{10}(d,p)B^{11}$. This group had an Hr of 448 kilogauss cm at the bombarding energy used. We have also made measurements on four reactions which emitted particles with considerably higher Hr values. These were the $N^{14}(d,\alpha)C^{12}$, $Li^6(d,\alpha)\alpha$, $B^{10}(d,\alpha)Be^8$, and $Be^9(d,t)Be^8$ reactions. The Hr values for the ground-state groups from these were approximately 480, 490, 510, and 511 kilogauss cm, respectively, corresponding to field strengths in the gap of the annular magnet in the range from 13,500 to 14,500 gauss. At these high fields the iron of the magnet is close to saturation, and it appears that under these conditions the magnetic field at the position of the fluxmeter is no longer accurately proportional to that in which the reaction products are focused. As a result, the measured fields for very large magnet currents have been found to be too high by as much as 0.2 percent. Thus, the Q-values for the four reactions observed under these conditions are too high by corresponding amounts. In the case of $Be^9(d,t)Be^8$, the error expressed in kilovolts is not so serious as in the case of the other reactions, since, for a given Hr, a triton has only one-third the energy of a proton or an alpha-particle. Hence, after a correction based on the results for the other reactions, the measured Q-value for $Be^9(d,t)Be^8$ is listed in Table I. However, for the other three reactions observed at high field strengths, more precise Q-values may be calculated from those of other reactions measured at lower fields, and these calculated values, together with those similarly calculated for certain other reactions, are listed separately in Table II.

The measured Q-value for the $N^{14}(d,\alpha)C^{12}$ reaction was 13.622 Mev after a 5-kev correction was made for surface contamination. This is 47 kev higher than the value of 13.575±0.012 Mev predicted from our measured Q-values for the $N^{14}(d, p)N^{15}$ and $N^{15}(p, \alpha)C^{12}$ reactions and 45 kev higher than the value of 13.577 ±0.012 Mev obtained from a combination of the $N^{14}(d, p)N^{15}$, $N^{15}(d, \alpha)C^{13}$, and $C^{12}(d, p)C^{13}$ Q-values. Additional indication that this calculated Q-value is more nearly correct than the one directly measured may be obtained from the Q-value of 9.137±0.006 Mev which we have measured for the $N^{14}(d, \alpha)C^{12*}$ alpha-group corresponding to the first excited state of C^{12}. The position of this state can be estimated as 4.431±0.011 Mev from the reported Q-value of 0.529±0.008 Mev[36] for the $N^{15}(p, \alpha)C^{12*}$ alpha-group corresponding to this level and from the present measurement of 4.960±0.007 Mev for the $N^{15}(p, \alpha)C^{12}$ ground-state transition. From these values, the ground-state $N^{14}(d, \alpha)C^{12}$ Q-value is found to be 13.568±0.012 Mev. The agreement of this value with those calculated from the other reaction cycles involving $N^{14}(d, p)N^{15}$ provides additional confirmation that, at the 442 kilogauss cm setting for the $N^{14}(d, p)N^{15}$ ground-state group that had the highest Hr of the groups involved in the calculations, the field measurements were not seriously affected by the effects of saturation.

Similarly, the measured Q-value of the $Li^6(d, \alpha)\alpha$ reaction was higher than the value calculated from the $Li^7(p, \alpha)\alpha$ and $Li^6(d, p)Li^7$ reaction energies. This calculated value is 22.359±0.017 Mev. In a series of measurements made on this reaction, the alpha-particle group whose Hr was in the region of 490 kilogauss cm had an energy which was consistently 0.1 to 0.4 percent higher than that calculated from the above Q-value.

The $B^{10}(d, \alpha)Be^8$ reaction energy can be calculated from two reaction cycles. From a combination of the $B^{10}(d, p)B^{11}$ and $B^{11}(p, \alpha)Be^8$ reactions, a $B^{10}(d, \alpha)Be^8$ Q-value of 17.802±0.016 Mev is calculated; from the $B^{10}(d, p)B^{11}$, $B^{11}(d, \alpha)Be^9$, and $Be^9(p, d)Be^8$ reactions, a value of 17.815±0.015 Mev is found. A weighted average of these results gives 17.809±0.015 Mev for the $B^{10}(d, \alpha)Be^8$ Q-value. The ground-state alpha-group from this reaction, observed at an Hr of 511 kilogauss cm, had an energy which was 0.25±0.11 percent higher than expected from the calculated value.

The $Be^9(d, t)Be^8$ ground-state triton group was observed at nearly the same Hr value as was the ground-state group from $B^{10}(d, \alpha)Be^8$. Using the result obtained for the $B^{10}(d, \alpha)Be^8$ group, a correction of −0.3±0.2 percent was applied to the observed energy of the triton group. Three measurements were made of the $Be^9(d, t)Be^8$ Q-value which agreed to ±7 kev. Corrections for surface contamination of less than 10 kev, estimated from previous measurements of the Li^{7++} and He^4 particles from the $Be^9(d, \alpha)Li^7$ reaction on the same target, were made to the measured Q-values. The weighted average of these measurements was 4.597±0.013 Mev for the $Be^9(d, t)Be^8$ Q-value, in agreement with the value of 4.592±0.008 Mev calculated from the $Be^9(p, d)Be^8$ and $D^2(d, p)T^3$ Q-values of 0.562±0.004 and 4.030±0.006 Mev.

TABLE II. Reaction energies calculated from Table I.

Reaction	Q-value (Mev)
$Li^6(d, \alpha)\alpha$	22.359±0.017
$Li^7(d, t)Li^6$	−0.989±0.009
$B^{10}(\alpha, p)C^{13}$	4.075±0.015
$B^{10}(d, \alpha)Be^8$	17.809±0.015
$N^{14}(d, \alpha)C^{12}$	13.577±0.012
$O^{17}(p, \alpha)N^{14}$	1.195±0.007
$O^{17}(d, t)O^{16}$	2.113±0.008
$Al^{27}(p, \alpha)Mg^{24}$	1.600±0.014
$Al^{27}(\alpha, p)Si^{30}$	2.374±0.015
$P^{31}(p, \alpha)Si^{28}$	1.924±0.022

In addition to those cases discussed above, the Q-values from Table I may be used to calculate the energy release of a number of other reactions. We have listed in Table II the Q-values obtained in this way for certain reactions with stable target nuclei. In some cases these reactions have not been observed. In general, the Q-values thus calculated are more accurate than those available or computed from present tables of nuclear masses.

V. MASSES OF THE LIGHT NUCLEI

There have been a number of compilations of nuclear masses based on nuclear-reaction Q-values and mass-spectrographic results, the most recent being that of Tollestrup, Fowler, and Lauritsen.[56] While the mass difference between the proton and deuteron, as determined by reaction data, is in good agreement with the value obtained from mass-spectrographic doublets, there has been a discrepancy between the values found for the mass of the alpha-particle. It has been suggested by Bainbridge[57] that this discrepancy may originate in the Q-values that have previously been available for the $Li^7(p, \alpha)\alpha$ and $Li^6(d, \alpha)\alpha$ reactions.

It is possible to calculate the mass difference $(2D^2-He^4)$ directly from nuclear data and to compare the value obtained with the result of mass-spectrographic doublet measurements. Thus, by adding the Q-values of the $Be^9(p, d)Be^8$ and $Be^8(\alpha)\alpha$ reactions and subtracting the result from the sum of the Q-values for the $Be^9(d, \alpha)Li^7$ and $Li^7(p, \alpha)\alpha$ reactions, $(2D^2-He^4) = 0.025599\pm0.000020$ amu is obtained. In this calculation, the value 0.093±0.005 Mev, from a weighted average of two results of 0.102±0.010 Mev[58] and 0.089±0.005 Mev,[13] was used for the $Be^8(\alpha)\alpha$ reaction. The remaining three reaction energies were taken from Table I. In the conversion from energy to mass units, the value 1 amu = 931±0.1 Mev was employed.[59] Similar results, agreeing within the experimental errors,

[56] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).
[57] K. T. Bainbridge, Phys. Rev. **81**, 146 (1951). We are indebted to Professor Bainbridge for the privilege of seeing his results in advance of publication.
[58] A. Hemmendinger, Phys. Rev. **75**, 1267 (1949).
[59] A. H. Wapstra, Physica **16**, 611 (1950).

are obtained from other cycles of the Q-values of the lighter nuclei listed in Tables I and II.

This value of 0.025599±0.000020 amu obtained for $(2D^2-He^4)$ from the more accurate nuclear data is in good agreement with the mass-spectrographic measurement of Ewald[60] and the recent unpublished result of Nier,[57] these values being 0.025604±0.000009 and 0.025612±0.000008 amu, respectively. The larger error associated with the result from disintegration data arises from the circumstance that, from the addition and subtraction of the reactions involved in the calculations, the mass of a single alpha-particle is equated to a combination of four Q-values. Using 2.014723±0.000005 amu for the mass of the deuteron[56] and the above value calculated for $(2D^2-He^4)$, the mass of He^4 is computed to be 4.003847±0.000022 amu.

The results obtained in the present work also make possible a more ambitious calculation for the He^4 mass, the result of which is that the mass of seven alpha-particles is expressed in terms of the deuteron mass and a sum of seven of the directly measured Q-values in Table I. Hence, it is possible to reduce considerably the probable error for the He^4 mass as compared with that calculated in the more limited cycles from which the mass of a single alpha-particle results. This calculation involves the $O^{16}(d,\alpha)N^{14}$, $N^{14}(d,p)N^{15}$, $N^{15}(d,\alpha)C^{13}$, $C^{13}(d,\alpha)B^{11}$, $B^{11}(d,\alpha)Be^9$, $Be^9(d,\alpha)Li^7$, and $Li^7(p,\alpha)\alpha$ reactions. Addition of these reactions leads to the equation:

$$He^4=(1/7)(O^{16}+6D^2-\Sigma Q),$$

where ΣQ is the sum of the Q-values of the seven reactions listed above. This calculation leads to 4.003863 ±0.000007 amu for the mass of He^4. In the estimation of the probable error, the systematic and random errors in the Q-value measurements have been considered separately. The important contributions to the probable error consisted of 4.3 kev from the uncertainty of the deuteron mass, 3.4 kev from the random errors, and 4.4 kev from systematic errors, such as those in the Hr for polonium alpha-particles and in the diameter of the magnet.

One other series of reactions has been used to calculate the mass of He^4. This series consists of $O^{16}(d,\alpha)N^{14}$, $N^{14}(d,p)N^{15}$, $N^{15}(d,\alpha)C^{13}$, $C^{13}(d,\alpha)B^{11}$, $B^{11}(p,\alpha)Be^8$, and $Be^8(\alpha)\alpha$. Addition of these reactions leads to the relation:

$$He^4=(1/6)(O^{16}+4D^2-\Sigma Q),$$

where ΣQ is the sum of the Q-values involved. This yields 4.003867±0.000006 amu for the mass of He^4, the estimate of the probable error containing contributions of 3.3 kev from the error in the deuteron mass and 3.2 and 2.8 kev from the random and systematic errors of the Q-value measurements.

A weighted average of these two results gives 4.003865±0.000007 amu for the mass of He^4. This result agrees within the probable errors with that obtained from the shorter cycle and is significantly lower than the previous value[56] of 4.003910 based on nuclear-reaction data. It remains somewhat higher than the value of 4.003842±0.000013 calculated by Bainbridge[57] from mass-spectra measurements, although the two results nearly overlap within the probable errors. While the probable error calculated for the result based on the present series of measurements may be somewhat too small in that unexpected compounding of errors may occur in the cycles used, it is to be noted that even if all the Q-values involved in the cycles based on O^{16} are increased to the limits allowed by the individual errors, the resulting He^4 mass is only reduced to 4.003854 and 4.003859 in the two cases. Also, if the discrepancy is to be attributed to an error in the determination of any single reaction energy, it is necessary to postulate an error of over 100 kev for one of the Q-values involved. Thus, the mass of He^4, as determined from nuclear data, appears to remain somewhat higher than that derived from mass spectra. The origin of this remaining discrepancy may be determined when the new Q-values reported here are also measured at other laboratories.

Together with other disintegration data, the results presented in Table I can be used to compile a table of nuclear masses based on O^{16} and the proton mass. Unfortunately, the lack of accurate Q-values for the reactions of the neon isotopes prevents the present extension of such a table beyond fluorine. It is hoped that neon targets suitable for precise experiments may become available so as to make such an extension possible.

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[60] H. Ewald, Z. Naturforsch. 5, 1 (1950).