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Atomic Masses from Accurate Measurements of Q Values[*][†]

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Precision measurements have been made of the ground-state Q values of the following nuclear reactions: $D(d,p)T$, $C^{12}(d,p)C^{13}$, $D(He^3,p)He^4$, $B^{10}(He^3,p)C^{12}$, $Be^9(He^3,p)B^{11}$, $B^{11}(He^3,p)C^{13}$, $C^{12}(He^3,p)N^{14}$, $B^{11}(He^3,d)C^{12}$, $B^{11}(d,\alpha)Be^9$, $B^{10}(d,\alpha)Be^8$, $Be^9(p,d)Be^8$, $Be^9(p,\alpha)Li^6$, $Be^9(d,t)Be^8$, $C^{13}(d,t)C^{12}$, and $B^{10}(\alpha,p)C^{13}$. There were 164 separate measurements made on these reactions. The standard deviations of the mean and a best estimate of error based on estimates of possible systematic errors were calculated. These errors ranged from ± 0.2 to ± 1.9 keV for the standard deviations and from ± 0.6 to ± 5.7 keV for the best estimates of error. Analysis of the direct measurements and reaction cycles between the measured reactions yielded best values for the $D(d,p)T$ and the $D(He^3,p)He^4$ Q values. The best values and the mass excesses of H and D and the T-He^3 mass difference as found in the 1964 Mass Table were used to calculate the He^3, T, and He^4 mass excesses. The mass excesses of Li^6, Be^8, Be^9, B^{10}, B^{11}, C^{13}, and N^{14} were then calculated from the Q-value measurements. Errors were calculated for these mass excesses based upon the standard deviations of the measured Q values and upon the estimates of possible systematic uncertainties. Analysis of consistency factors indicates that the actual errors lie between these two error estimates. These results constitute the most accurate systematic determination of these masses from Q-value data.

INTRODUCTION

In general, the measurements of nuclear-reaction Q values in the low-mass region have experimental errors of 3 to 10 keV. Mass-spectroscopic doublet measurements of masses in this region have errors ranging from 0.3 to 8 keV. The mass table of Mattauch *et al.*,[1] which incorporates both mass spectroscopic and nuclear reaction data in order to obtain a "best value" of the masses, quotes errors for the masses corresponding to energy uncertainties usually less than 1 keV. The self-consistent set of Q values[2] calculated from the masses has errors of the order of 1.5 keV or less. The stated uncertainties in the tabulations are significantly less than those of either of the sources of input data. Consequently, a direct check of these mass table values would be valuable. It was felt that with the improvement in technique developed over the past 10 years, improved current supplies, and averaging of a large number of very careful measurements, we could reduce the errors in the Q values by a factor of about 5. A strict comparison could then be made between the mass table, mass spectrometric measurements and a set of Q-value measurements. Such a comparison is one of the aims of this work.

Most Q-value measurements involve two of the nuclides H, D, T, He^3, or He^4 as the impinging and outgoing particles. Since the masses of these particles must be known to calculate the masses of heavier nuclides from Q values, it is imperative to minimize uncertainties in these masses. Although the mass table quotes small errors for the triton mass (± 0.21 keV), the He^3 mass (± 0.21 keV) and the He^4 mass (± 0.42 keV), direct measurements of these quantities differ from one another by larger amounts. Determination of the He^3 and triton masses done at Brookhaven[3,4] and at Harvard[5] differ from one another by 2.83 μu and 2.55 μu, respectively, while the root-mean-square (rms) sums of the stated errors are 0.58 and 0.88 μu, respectively ("u" represents the unified atomic mass unit based on the mass of C^{12}). Another determination of the He^3 mass done at the Russian Academy of Sciences[6] is about 38 μu lower than either the Harvard or Brookhaven numbers. The He^4 mass has been measured more extensively; however, the differences between the values obtained are frequently larger than should be expected from stated experimental errors. On the other hand, the agreement between experimenters on the deuteron and proton mass and the T-He^3 mass difference is quite good[3,4,7–11] and all agree well with the mass table.

A major aim of the present work was to determine the masses of the T, He^3, and He^4 nuclides to high accuracy and thus provide a firm foundation for precision Q-value measurements involving these particles. Two of the Q values measured directly in this work involve only these particles and the proton and deuteron: the $D(d,p)T$ and $D(He^3,p)He^4$ reactions. Because of the excellent agreement of previous measurements, it was felt that the use of the mass table values for the H and D masses

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and the T-He^3 mass difference should introduce negligible inaccuracy in the results. These masses, the direct Q measurements and values obtained for these Q values from five reaction cycles constructed from other Q values measured in this work are used to calculate the T, He^3, and He^4 masses. Four precision measurements of the $D(d,p)T$ Q value have been made[12–15] which agree reasonably well with one another; however, the stated uncertainties are fairly large. The University of Mexico group[15] has also measured the $D(He^3,p)He^4$ Q value but with a large uncertainty.

A third aim of this work was to provide a secondary energy standard with an energy well above that of the alpha particles from Po^{210}. Need for such a standard has become more acute as the energy rating of electrostatic accelerators has increased. A nuclear reaction with a very high Q value, which is known with high accuracy, can be used to produce particles of well-known energy. Two of the measured reactions are useful for this purpose. These are the $B^{10}(He^3,p)C^{12}$ and $B^{10}(d,\alpha)Be^8$ reactions with Q values of 19.7 and 17.8 MeV, respectively.

It is well to point out that this work is part of a long-term effort to measure many Q values in a systematic manner. It is important that the reaction data to be compared with the doublet data come from one laboratory with continuously evolving equipment and techniques so that they are subject to the same systematic errors. With such a set of data one may hope to gain some insight into the systematic errors which may be present in either system. Although precision Q values in this mass region (up to mass 14) have been measured by several other laboratories,[16–23] the work done at MIT[13] and the University of Mexico[15,24] is the most systematic.

In the case of the MIT work, nearly all of these Q's were measured prior to 1954 with an 180° annular magnet of the Cockcroft type. This device requires a series of magnetic field settings in order to measure input and output particle energies, and it is necessary to assume that the ratio of the average field along the particle trajectory to the field at the fluxmeter probe remained constant for all fields.

The Q-value measurements at the University of Mexico were carried out with a broad-range magnetic spectrograph similar in design to the one used at this laboratory. The relatively small spectrograph radius, however, required fairly high fields and saturation effects apparently resulted. A correction factor for field saturation improved the situation somewhat, but large discrepancies between these Q values and accurately known masses remain, particularly in those reactions with Q values over 10 MeV.

Two of the 15 reaction energies measured in this work are measured for the first time, and all measurements have stated errors smaller than those quoted in the MIT and University of Mexico work. Both the standard deviation and a best estimate of error is given. The best estimate of error was obtained by combination of the estimated probable systematic errors present in each independent measurement with the random error.

The organization of this work is as follows: certain details of experimental techniques will be presented, the method of assignment of the Q-value errors will be outlined, the results of the Q-value measurements will be presented and comparisons made with previous measurements. Sets of reaction cycles will be presented which yield "best values" for the $D(d,p)T$ and $D(He^3,p)He^4$ Q values. These best values will be used to calculate the mass excesses of the T, He^3, and He^4 nuclides; comparisons with other work will be presented. The masses of Li^6, Be^8, Be^9, B^{10}, B^{11}, C^{13}, and N^{14} will be calculated and comparisons will be presented.

EXPERIMENTAL PROCEDURE

Standard procedures for measuring Q values with broad-range spectrographs and electrostatic accelerators have been described many times. One example pertinent to this work is referred to.[25] The type of broad-range spectrograph used in these measurements has been described in detail by Browne and Buechner[26] and by Zimmerman,[27] so only some important details will be discussed.

The spectrograph is calibrated with alpha particles (Po-α) emitted in the decay of Po^{210} and the value 5.3045 ± 0.0005 MeV is used[28] for the energy; this is an average of 6 absolute measurements made over the last

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30 years. Examining essentially the same data, Wapstra[29] suggests the value 5.30451 ± 0.00047 MeV when the most recently recommended value for the faraday[30] and the mass-table[1] values for the reaction particles are used to convert from magnetic rigidity to energy. In the present work this conversion was made using the tables of Enge.[31] Use of the newer values for the faraday[30] and the particle masses[1] would give a reduction of 0.003% (0.15 keV) in our adopted value of the (Po-α) energy. A proportionate reduction would be made in the Q values given below. These differences are small compared to the experimental uncertainties. In accord with our long term effort to measure many Q values in a systematic manner we have chosen to retain our adopted standards.

The broad energy range of the spectrograph is especially valuable in measuring Q values in that it makes it possible to measure the energies of the reaction particles and the elastically scattered particle used to find the input energy, without changing the field. This minimizes the error in the Q value arising from differential hysteresis. In measuring a given particle energy with the Notre Dame spectrograph, a discrepancy of the order of 12 keV out of 5.3 MeV was once found[32] depending on whether the spectrograph field was raised or lowered to the "proper" (as indicated by the fluxmeter) field. Previous to this work, the method used to combat differential hysteresis was simply to approach the correct field from below and to avoid any appreciable overshoot. Periodic checks routinely agreed with the calibration to better than $\pm 1/1000$ in energy. In the course of the present measurements many Po-α runs were made which generally agreed to this precision, i.e., ± 4 keV out of 5.3045 MeV.

To further reduce the differential hysteresis, a field cycling process was developed in order to construct a more uniform magnetic history for the iron. A calibration of the spectrograph was made using this cycling procedure before each Po-α exposure. Check runs indicate that the inconsistency of the calibration has been considerably reduced. The worst case to date was a Po-α group which was 2 keV high, whereas most of the rest lie within about ± 0.5 keV, a factor of at least 3 improvement over the precycling results. Therefore, we feel that with cycling we can reproduce the whole calibration curve of the spectrograph to better than 1 part in 2500 in energy.

There is convincing evidence that the shape of the calibration curve (the plot of trajectory radius, ρ versus position along the plate, D) remains even more constant. This evidence is as follows: Before this work, the spectrograph had been completely recalibrated twice. Although the position of the calibration curve relative to the ρ-ρ (theoretical) baseline shifted up or down, the shape was largely retained. An examination of the calibration at higher fields was also done. In this case, rather than a Po-α source, the $B^{10}(d,\alpha)Be^8$ reaction was used to provide output particles of $B\rho = 517$ kG cm. The reaction group was moved along the plate in a manner similar to ordinary calibration, requiring a field of 11.6 kG at the lowest D value. The average deviation of the reaction-generated points from the calibration curve based on Po-α is equal to 0.031 mm. At a trajectory radius of 52 cm, this represents an error of about 0.012% in particle energy. The agreement between the precycling and cycled field calibration curve shapes is even better. The effect of the cycling technique was to shift the calibration curve upward by an average of 0.2 mm. The average difference between the old calibration curve and the new calibration points when uniformly shifted upward by 0.2 mm, is 0.025 mm. At a radius of 52 cm this represents an energy error of 0.008%. Figure 1 shows the precycling calibration curve, the cycled field calibration curve and points for the $\beta\rho = 517$ kG cm group. The agreement in shape of the 3 curves strongly suggests that the curve shape is constant to something like the above average deviations, and quite less sensitive to differential hysteresis effects than the absolute calibration itself. A magnetic field above 11.6 kG was used in only three of the 164 separate measurements reported here.

If it is indeed true that the calibration curve shape is constant over its whole range for different momentum particles, then we need only locate the absolute position of the curve at some point to obtain the exact value of the curve at all points. This procedure was followed in these measurements. In most cases, a Po-α group was placed on the plate after the spectrograph field was set

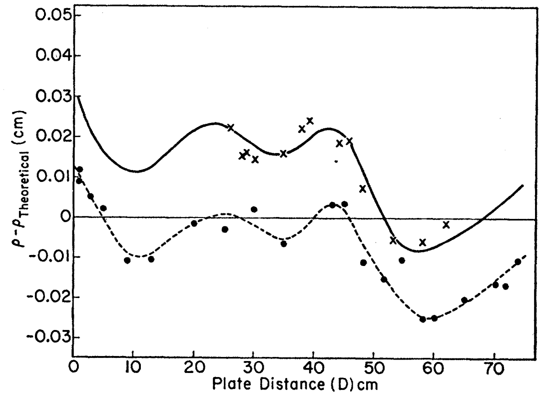

FIG. 1. The spectrograph calibration curves, showing the agreement in curve shape between the new cycled-field calibration curve, the precycling curve, and a set of points taken with a $B\rho = 517$ kG cm particle from the $B^{10}(d,\alpha)Be^8$ reaction. These last are normalized to the precycling curve. Solid line—precycling calibration curve; dashed line—cycled field calibration curve; solid circles—cycled field calibration points; crosses—$B\rho = 517$ kG cm particle points.

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and stabilized. This Po-α group was used to calculate a correction, $d\rho$, to the trajectory radius, which was added to all of the trajectory radii involved in the measurement thereby greatly reducing the calibration errors. This procedure will be referred to as calibrating the field.

In a large number of runs, the kinematics of the reaction precluded placing a Po-α group on the plate with all of the rest of the groups of interest. In this case, some secondary calibration methods were used. For example, the protons from the $B^{10}(He^3,p)C^{12}$ reaction were too energetic to be observed at the same field setting as the He^{3++} particles elastically scattered from gold. It was however, possible to record the singly charged He^{3+} at the same field as the protons, but this field was too high to allow the observation of a Po-α group.

The input particle was used to calibrate the high field. The field was set so that the Po-α group was at the top of the plate, while the He^{3++} group scattered from gold was near the lower end. The Po-α group was recorded and two or three runs made to record the elastically scattered groups. Then the field was raised to place the energetic reaction protons near the top while the elastically scattered, singly charged He^{3+} particles were at the low end of the plate. The Po-α was used to calibrate the lower field setting to accurately obtain the input energy. Assuming the input energy constant, the He^{3+} group having the same energy but twice the $B\rho$ was used to calculate the trajectory correction, $d\rho$, which was used to calibrate the higher field.

The $B^{10}(He^3,p)C^{12}$ Q value is an example of the worst case, requiring us to assume that the input energy remained constant while changing the spectrograph field, and that the singly and doubly charged He^3 ions had the same energy after being scattered from the gold. Justification for the first assumption will be given below; however, variations in the input energy between the low- and high-field runs would seem to introduce random rather than systematic errors. The second assumption amounts to ignoring atomic effects.

Other reactions required only the first assumption since it was possible to work with only one charge state of the input particle. Constant-energy input particles, however, played an important part in the philosophy of field calibration used for the measurements in this work.

Input Particles

The particle beam from the Notre Dame electrostatic accelerator is magnetically analyzed by a symmetric 30° analyzing magnet with geometric energy resolution of 1200. The energy of the input particle was determined by elastic scattering into the spectrograph rather than by using the analyzing magnet calibration. Therefore, the chief requirement on the analyzer field is stability. In practice we observe that the stabilization of the accelerator holds the beam centered between the slits quite well.

By setting the accelerator energy and beam current to the desired values and allowing the ion source and the beam handling controls to come to equilibrium, the observed spread in input energies as measured by elastic scattering is typically of the order of 0.01% in energy.

Since the coefficient of the input energy term in the Q equation is always less than one, uncertainties in the input energy are not usually great sources of error *per se*; however, when the invariance of the input energy is relied upon to calibrate a higher spectrograph field, this uncertainty may contribute sizably to the error. Consequently, every effort was made to avoid unnecessary adjustment of the beam parameters.

Reaction Angle

The method of measuring the reaction angle and the marking of the angle scale in 5° intervals has been described earlier.[32] Except for the $D(d,p)T$ and $C^{12}(d,p)C^{13}$ reactions all measurements were made at multiples of 5°. Precise knowledge of the reaction angle is most important in the measurement of the $D(d,p)T$ and the $D(He^3,p)He^4$ Q values. These exhibit high center-of-mass motion and consequently are quite sensitive to any error in reaction angle. For example, in a typical measurement on $D(d,p)T$ at a reaction angle of 58° the angle sensitivity is 1.3 keV per min. These extreme kinematic effects are the largest source of error in this reaction.

In normal operation, the particle groups are recorded along a zone one cm wide on the nuclear track plate. At a plate position of 52 cm, this 1-cm zone width subtends an angle of 18.8 min. Therefore, for the highly kinematic reactions, the entire zone could not be used, only a thin strip 1 or $\frac{1}{2}$ mm wide in the center of the zone was counted. The 1-mm strip subtends less than 2 min which appears to introduce no effect in most measurements. This zone-center counting was used any time we could observe a shifting of the peak position across the zone.

Targets

The target materials used were natural boron, enriched B^{10} and B^{11}, beryllium metal, natural carbon, deuterated paraffin, and gold. The targets were made by vacuum evaporation using resistance heating, or, in the case of the boron targets, by electron bombardment. Target material was usually deposited on a backing material, either Formvar or carbon foils, although some self-supporting foils were also used. In order to avoid errors from formation of surface layers on the targets, every effort was made to use freshly prepared targets throughout.

For some targets, particularly those employed with

He^3 or He^4 input particles, the reaction or elastically scattered particle group exhibited thick-target characteristics rather than thin. Since the spectrograph was calibrated for a thin-target group shape, a correction was made to the thick-target group shape. From a number of Po-α calibration runs a curve has been constructed which gives the proper slope of the group front edge as a function of D. For a thick target, the point on the front edge at one-half the plateau height corresponds to the center of the thin-target peak of the same energy. Therefore, using the curve to obtain the proper thin-target peak-to-third-height distance we construct the thin-target peak with the proper slope centered at this point. The third height of this constructed peak is taken to be the peak position.

The distinction between thick and thin is often tenuous, and judgment must be used. The usual criterion is whether the group is flat on top, though again this is not always clear cut. Questionable group shape is often an important uncertainty.

The high melting point of the boron made us consider the possibility of an inert carbon layer put over the boron at the time the targets were made, since the boron was always evaporated from a carbon vessel. These targets were checked for a carbon layer by elastically scattering particles from them. The input energy was calculated from the elastic groups from boron and carbon. If there had been a surface layer of carbon, the energy calculated from the carbon would be higher than that from the boron. There was, however, no evidence for this sort of carbon layer.

In a previous work done here[25] inverse Q values involving α particles were measured. In most of these any target layer effects would make disagreement between the inverse Q's quite large, whereas in fact agreement between the Q's was excellent, supporting the conclusion that inert layer effects are not generally troublesome at this laboratory.

RESULTS

Treatment of the Data and Error Analysis

After making several measurements of a Q value, varying the parameters as much as is reasonably convenient, we are left with a number of values for the Q. In order to arrive at the best value, a weighted mean was calculated for the reaction using the formula

$$Q_{\mathrm{av}}=\sum w_iQ_i/\sum w_i,$$

where Q_i is the result of a given measurement, and w_i is the weighting factor applied.

The weighting factors depend chiefly on the manner in which the spectrograph field was calibrated for that particular measurement. If we were forced to rely upon the spectrograph calibration alone, the weighting factor was $\frac{1}{4}$ that for a well calibrated field. Other considerations were group shape and agreement among input energy determinations made before and after the run. The weighting factors used gave values differing only slightly from the unweighted means.

The standard deviation of the mean was calculated using the formula

$$\sigma_m=[\sum \delta_i^2w_i/(N-1)\sum w_i]^{1/2},$$

where δ_i is the deviation of a measurement from the mean and N is the number of runs. The internal error was also calculated for each reaction from the formula

$$e_{\mathrm{int}}=[\sum (1/\Delta E_i)^2]^{-1/2}.$$

The ΔE_i is the estimated random error present in each measurement. This number is calculated by taking the square root of the sum of the squares of the various random errors in each measurement. These are calibration error, error in setting the reaction angle, counting and plotting error and any other calculable error, such as an error in group shape.

To obtain the calibration error, a percentage of the Q value was taken. This percentage varied with the method of calibration of the field. When relying on the fluxmeter and spectrograph calibration alone, the error was taken to be 0.1% of the measured Q; for a cycled field using the new cycled field calibration, 0.04%; for indirectly calibrated field using elastic scattering, 0.04 or 0.03% depending on the agreement of the elastic scattering groups; for a field calibrated directly by a Po-α group taken at the same field setting as the reaction and elastic groups, 0.02%; and for a possible gross error, for example, the lack of a spectrograph fluxmeter pip while running the reaction, 0.2% of the measured Q.

The random error associated with the reaction angle setting was taken to be ± 2 min of arc.[23]

The counting and plotting error is estimated to be 0.1 mm in the D value.

Since the spectrograph is calibrated for groups which exhibit a thin-target shape, the possibility exists that we may introduce errors in making the thick-target correction outlined above. The random error associated with group shape was taken to be one-third of the change in Q resulting from the correction.

We now have two values for the random error, σ_m and e_{int}. Some experimenters prefer to quote the standard deviation of the mean as almost the total error of the experiment. This philosophy holds that quantitative estimation of systematic errors is generally not meaningful. In this work, an effort was made to estimate the systematic errors present in each measurement.

To quote an error which we hope corresponds reasonably well to the actual unknown and unknowable error of the Q value, the larger of the two measures of random error, σ_m or e_{int}, was combined with the best estimates for the systematic errors. These estimates are 0.01% of the Q value for a possible systematic error in the calibration of the spectrograph, ± 2 min of arc in the reaction angle scale, and $\frac{1}{4}$ to $\frac{1}{3}$ of any correction to Q owing to a conversion from thick-target to thin-target

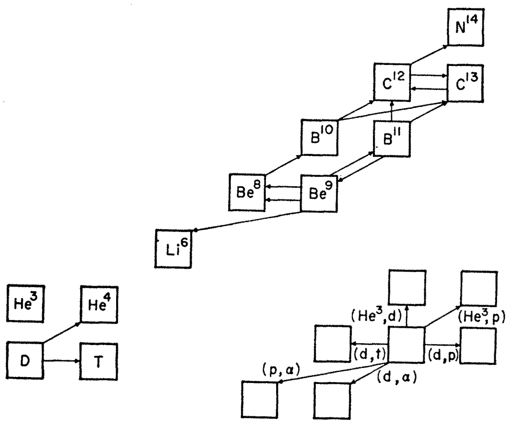

FIG. 2. Schematic representation of the reactions measured in this work. Each line linking two nuclides indicates a Q value. The direction of the line is from target nucleus to residual nucleus. The key to the reaction particles involved in these reactions is at the lower right; the central nucleus is the target nucleus.

group shape. In order to compare these results with those obtained at other laboratories, the error in the Po-α calibration energy must be combined as a possible systematic error. This value is 0.0094% of the measured Q.

We now have two errors to be quoted with the measured Q value, the standard deviation of the mean, σ_m, and a best estimate of total error. The evaluation of this best error involves some subjective judgments, but it was felt that it reflected a realistic evaluation of how well the measurement had been made.

Results of the Q-Value Measurements

The Q values measured in this work are graphically displayed in Fig. 2. Here each line connecting two of the nuclides denotes one of the measured Q values.

Table I. Results of Q-value measurements for $D(d,p)T$ and $C^{12}(d,p)C^{13}$. Energy units are keV. All values are based on a Po^{210} alpha-particle energy of 5304.5 keV. Internal errors are based on the estimate of the random error in each measurement.

	$D(d,p)T$				$C^{12}(d,p)C^{13}$		
Run	Input energy	Angle of observation (deg)	Q	Run	Input energy	Angle of observation (deg)	Q
1	2660.2	58	4035.9[a]	1	1995.6	60	2722.2
2	2660.2	58	4034.7[a]	2	1994.8	60	2720.8
3	2658.4	58	4034.3[a]	3	1994.8	60	2722.7
4	2658.4	58	4034.3[a]	4	2500.7	60	2721.6
5	2000.4	58	4033.5[b]	5	2660.2	58	2723.3
6	2000.4	58	4032.2[c]	6	2660.2	58	2722.8
7	1995.2	60	4033.6	7	2658.4	58	2723.1
8	2992.1	60	4032.8	8	2658.4	58	2723.9
9	2991.8	60	4031.9	9	2992.1	60	2721.1
10	1706.2	70	4033.6	10	2992.1	60	2721.1
11	2000.3	70	4033.3	11	1706.2	60	2724.8
12	2000.3	70	4034.5	12	2000.3	70	2721.1
13	2000.3	70	4036.9	13	2000.3	70	2720.5
14	2000.3	70	4035.7	14	2000.3	70	2723.3
15	2666.6	58	4035.0[a]	15	2000.3	70	2722.4
16	2666.6	58	4035.9[a]	Weighted mean			2722.3
17	2661.1	58	4032.8[a]	Standard deviation of mean, σ_m			0.31
18	2661.1	58	4031.3[a]	Internal error, e_{int}			0.18
19	2661.8	58	4033.4[a]				
Weighted mean			4033.7				
Standard deviation of mean, σ_m			0.30				
Internal error, e_{int}			0.33				

[a] Q value corrected by an amount corresponding to 2.9 min of arc in observation angle, as determined in run 5 by observation of tritons.

[b] Reaction angle measured using tritons, correction = +2.9 min.

[c] Reaction angle measured using tritons, correction = +2.4 min.

TABLE II. Results of Q-value measurements for $D(He^3,p)He^4$ and $B^{10}(He^3,p)C^{12}$. Energy units are keV.

	$D(He^3,p)He^4$				$B^{10}(He^3,p)C^{12}$		
Run	Input energy	Angle of observation (deg)	Q	Run	Input energy	Angle of observation (deg)	Q
1	3499.9	140	18351.8	1	3981.1	120	19690.2
2	3997.5	140	18350.0	2	3117.0	140	19694.6
3	3498.8	140	18367.1	3	3980.2	120	19680.7
4	3997.5	140	18339.8	4	3981.5	135	19683.0
5	2498.3	140	18348.3	5	3981.5	135	19704.8
6	2783.3	140	18352.2	6	3981.5	135	19693.0
7	3497.8	140	18352.5	7	3981.5	135	19690.2
8	3998.2	140	18348.2	8	3980.0	135	19699.7
9	2998.7	140	18341.2	9	3980.7	135	19698.7
10	2997.4	60	18344.1	10	3980.7	135	19702.0
Weighted mean			18350.1	11	3100.4	130	19688.2
Standard deviation of mean, σ_m			1.9	12	3100.4	130	19690.0
Internal error, e_{int}			1.6	13	3997.2	135	19694.2
				14	3997.2	135	19697.1
				15	3997.2	135	19692.2
				Weighted mean			19694.5
				Standard deviation of mean, σ_m			1.5
				Internal error, e_{int}			2.0

TABLE III. Results of Q-value measurements for $Be^9(He^3,p)B^{11}$, $B^{11}(He^3,p)C^{13}$, $C^{12}(He^3,p)N^{14}$, and $B^{11}(He^3,d)C^{12}$. Energy units are keV.

	$Be^9(He^3,p)B^{11}$				$B^{11}(He^3,p)C^{13}$		
Run	Input energy	Angle of observation (deg)		Run	Input energy	Angle of observation (deg)	Q
1	2003.0	135	10322.8	1	4000.1	135	13188.8
2	2002.0	135	10319.7	2	3994.8	140	13181.1
3	3000.8	90	10333.1	3	3503.8	140	13186.5
4	3499.9	135	10319.6	4	2999.9	140	13190.9
5	3005.5	90	10321.4	5	3993.8	140	13183.6
6	3497.7	135	10323.2	6	2999.8	140	13185.7
7	3999.7	110	10321.4	7	3496.4	140	13185.5
8	3999.7	110	10321.6	Weighted mean			13185.4
Weighted mean			10322.1	Standard deviation of mean, σ_m			0.9
Standard deviation of mean, σ_m			1.2	Internal error, e_{int}			2.0
Internal error, e_{int}			0.5				
	$C^{12}(He^3,p)N^{14}$				$B^{11}(He^3,d)C^{12}$		
Run	Input energy	Angle of observation (deg)	Q	Run	Input energy	Angle of observation (deg)	Q
1	3498.8	140	4778.3	1	4000.1	135	10470.7
2	3997.5	140	4777.0	2	3994.8	140	10460.1
3	2498.3	140	4775.8	3	3503.8	140	10474.4
4	3497.8	140	4775.1	4	2999.9	140	10467.5
5	3998.2	140	4777.0	5	3993.8	140	10474.1
6	3499.9	140	4775.3	6	2999.8	140	10466.4
7	3997.5	140	4775.8	7	3496.4	140	10472.5
Weighted mean			4776.3	Weighted mean			10469.7
Standard deviation of mean, σ_m			0.4	Standard deviation of mean, σ_m			1.6
Internal error, e_{int}			0.8	Internal error, e_{int}			1.9

The direction of the arrow shows the direction from the target to the residual nucleus.

In all, 164 individual measurements were made of these 15 Q values. An attempt was made to vary the input parameters as much as was reasonably convenient in order to randomize as many of the errors as possible. Tables I through VI give in detail the input parameters for each run as well as the resultant Q value. The reactions appearing in the tables are as follows: $D(d,p)T$, $C^{12}(d,p)C^{13}$, $D(He^3,p)He^4$, $B^{10}(He^3,p)C^{12}$, $Be^9(He^3,p)B^{11}$, $B^{11}(He^3,p)C^{13}$, $C^{12}(He^3,p)N^{14}$, $B^{11}(He^3,d)C^{12}$, $B^{11}(d,\alpha)Be^9$, $B^{10}(d,\alpha)Be^8$, $Be^9(p,d)Be^8$, $Be^9(d,t)Be^8$, $C^{13}(d,t)C^{12}$, and $B^{10}(\alpha,p)C^{13}$. The weighted mean, weighted standard deviation of the mean, and the internal error are also presented in the tables. Since it was reported on previously,[25] the $Be^9(p,\alpha)Li^6$ reaction is not included in the tables.

TABLE IV. Results of Q-value measurements for $B^{11}(d,\alpha)Be^9$ and $B^{10}(d,\alpha)Be^8$. Energy units are keV.

	$B^{11}(d,\alpha)Be^9$				$B^{10}(d,\alpha)Be^8$		
Run	Input energy	Angle of observation (deg)	Q	Run	Input energy	Angle of observation (deg)	Q
1	2998.3	135	8029.8	1	2998.7	120	17824.6
2	2997.6	135	8035.4	2	3497.7	125	17814.3
3	2998.7	120	8028.7	3	3497.7	140	17821.3
4	3497.7	125	8027.1	4	2998.5	135	17815.6
5	3497.7	140	8023.0	5	3999.5	130	17819.1
6	2998.5	135	8031.8	6	3999.5	140	17816.6
7	3999.5	140	8025.5	7[a]	2001.7	90	17821.0
8	3999.5	130	8034.6	8			17821.7
Weighted mean			8029.7	9			17819.9
Standard deviation of mean, σ_m			1.5	10			17817.7
Internal error, e_{int}			1.2	11			18218.2
				12			17814.4
				13			17816.1
				14			17820.9
				15			17818.4
				16			17822.5
				17			17820.7
				18			17816.3
				19			17815.1
				Weighted mean			17818.6
				Standard deviation of mean, σ_m			1.0
				Internal error, e_{int}			2.0

[a] Runs 7 through 19 were taken at the same observation angle and with the same input energy. In the calculation of the standard deviation of the mean, each of these runs was considered as $\frac{1}{3}$ of an independent run. Therefore, in this calculation the number of runs was taken to be 10.33.

TABLE V. Results of Q-value measurements for $Be^9(p,d)Be^8$ and $Be^9(d,t)Be^8$. Energy units are keV.

	$Be^9(p,d)Be^8$				$Be^9(d,t)Be^8$		
Run	Input energy	Angle of observation (deg)	Q	Run	Input energy	Angle of observation (deg)	Q
1	3001.0	90	559.8	1	3489.2	100	4590.4
2	3000.6	90	559.6	2	3498.8	100	4591.3
3	2502.7	110	559.8	3	3498.8	100	4593.6
4	2502.0	110	560.5	4	3199.7	110	4592.5
5	3002.6	70	559.4	5	3199.7	110	4592.2
6	3002.5	70	559.5	6	3199.7	110	4591.2
7	3002.0	70	559.0	7	3199.7	110	4591.5
8	3002.5	110	559.2	8	3199.7	110	4591.2
9	3002.3	110	558.2	9	3499.0	110	4591.4
10	3002.0	110	560.9	10	3499.0	110	4591.8
Weighted mean			559.6	Weighted mean			4591.7
Standard deviation of mean, σ_m			0.22	Standard deviation of mean, σ_m			0.29
Internal error, e_{int}			0.28	Internal error, e_{int}			1.5

TABLE VI. Results of Q-value measurements for $C^{13}(d,t)C^{12}$ and $B^{10}(\alpha,p)C^{13}$. Energy units are keV.

	$C^{13}(d,t)C^{12}$				$B^{10}(\alpha,p)C^{13}$		
Run	Input energy	Angle of observation (deg)		Run	Input energy	Angle of observation (deg)	Q
1	1994.9	130	1311.6	1	2498.0	80	4067.5
2	2500.7	60	1308.5	2	1997.6	75	4064.6
3	2001.7	130	1312.0	3	1997.6	90	4060.9
4	2502.3	58	1310.6	4	1997.6	95	4060.8
5	2991.9	70	1309.8	Weighted mean			4063.4
6	2990.7	70	1310.0	Standard deviation of mean σ_m			1.3
7	2992.5	70	1310.2	Internal error, e_{int}			1.6
8	2503.6	90	1311.7				
9	2991.1	70	1311.6				
10	2992.1	70	1311.9				
Weighted mean			1310.9				
Standard deviation of mean, σ_m			0.31				
Internal error, e_{int}			0.30				

Table VII gives a summary of the Q-value errors, including those that are statistically based, σ_m and e_{int}, and the estimates of the systematic errors. The combination of these uncertainties, the best estimate of error, is also presented.

The majority of the Q values were measured almost entirely as outlined in the section on Experimental Procedure; however, some of the measurements merit comment.

The kinematics of the $D(d,p)T$ reaction are such that with an input energy of 2.66 MeV and a reaction angle of 58° both the elastically scattered deuterons and the reaction protons have nearly the same $B\rho$ as that of a Po-α particle. For this reason, a large number of runs were taken with these input parameters. Since the spectrograph angle scale is marked only every 5°, a rule

TABLE VII. Summary of Q-value errors, including statistical uncertainties and estimates of systematic uncertainties. All uncertainties are in keV. The result of the combination of the estimated systematic uncertainties with the larger of σ_m or e_{int} is given as the best estimate of error.

			Estimated systematic uncertainties				
Reaction	σ_m	e_{int}	Calibration	Reaction angle	Group shape	Po-α	Best estimate of error
$D(d,p)T$	0.30	0.33	0.4	1.6		0.4	1.7
$C^{12}(d,p)C^{13}$	0.31	0.18	0.3	0.3		0.3	0.61
$D(He^3,p)He^4$	1.9	1.6	1.8	2.3	0.3	1.7	3.9
$B^{10}(He^3,p)C^{12}$	1.5	2.0	2.0	1.0		1.9	3.6
$Be^9(He^3,p)B^{11}$	1.2	0.5	1.0	1.0	0.8	1.0	2.3
$B^{11}(He^3,p)C^{13}$	0.9	2.0	3.0	0.7	1.0	1.3	4.0
$C^{12}(He^3,p)N^{14}$	0.4	0.8	1.0	0.5	0.45	0.3	1.5
$B^{11}(He^3,d)C^{12}$	1.6	1.9	4.2	1.0	3.0	1.0	5.7
$B^{11}(d,\alpha)Be^9$	1.5	1.2	0.8	1.1	1.8	0.75	2.8
$B^{10}(d,\alpha)Be^8$	1.0	2.0	1.8	2.0	1.6	1.7	4.1
$Be^9(p,d)Be^8$	0.22	0.28	0.17	0.5		0.05	0.63
$Be^9(p,\alpha)Li^6$	0.2		0.4	1.4	1.0	0.2	1.8
$Be^9(d,t)Be^8$	0.3	1.5	2.3	1.3		0.4	3.1
$C^{13}(d,t)C^{12}$	0.31	0.30	0.13	0.6		0.1	0.7
$B^{10}(\alpha,p)C^{13}$	1.3	1.6	0.8	0.6	1.5	0.4	2.4

was used to interpolate between 55° and 60°. As 11 of the 19 runs on this reaction were taken at 58° an attempt was made to measure this angle by use of the reaction itself.

At 2.0 MeV and 58° it is possible to see both the protons from the reaction and the tritons as well. Since the sensitivity of the triton energy to angle is about three times that of the proton energy, any deviation of the spectrograph angle from the indicated angle will produce a larger discrepancy in the Q value measured from the triton energy than in that measured from the proton energy. Extremely long exposures were made to accumulate enough triton tracks to achieve a reasonable group shape. In one case there were enough tritons to make it feasible to count only a $\frac{1}{4}$-mm strip in the center of the zone, while in another the group was counted along a $\frac{1}{2}$-mm strip.

Q values were calculated considering both the tritons and protons as the outgoing particles. The correction to the reaction angle needed to make both these Q values the same was calculated. The observed $\Delta\theta$ was 2.9 min for the group counted along the $\frac{1}{4}$-mm strip, and 2.4 min for the group counted along the $\frac{1}{2}$-mm strip. The angular correction of 2.9 min was applied for all of the Q values measured at 58°.

The largest estimated systematic error in this reaction is the angular uncertainty. In spite of the measured correction, this uncertainty was still taken to be ± 2 min of arc, since uncertainties in the position of the triton group, owing to poor statistics and thick-target shape, precluded a highly precise angle correction.

The $B^{11}(He^3,p)N^{14}$ and $B^{11}(He^3,d)C^{12}$ reactions were measured at the same time. That is, the input energy, observation angles, and spectrograph fields were adjusted so that both the deuteron group and the proton group fell on the plate. This required very large magnetic fields, as the deuteron $B\rho$ ranged up to 645 kG cm. On three occasions the proton resonance fluxmeter was incorrectly set in such a manner that the spectrograph field was considerably higher than planned. Fortunately in these cases it was possible to obtain the value of the field from calibration points; however, large errors were assigned to these runs since there is doubt about the calibration curve shape at such a high field ($B\sim 12$ kG). The calibration errors assigned these reactions were 4.2 keV in the case of the deuteron reaction and 3 keV for the protons. The basis of these assignments was 0.02% of the measured Q value for the protons and 0.04% for the deuterons. Though both groups were measured at the same field, it was felt that the much higher $B\rho$ of the deuterons warranted the larger error assignment.

The $C^{12}(He^3,p)N^{14}$ reaction was measured concurrently with the $D(He^3,p)He^4$ reaction. In all cases the elastically scattered group exhibited a thick-target shape, so the appropriate correction was applied. This resulted in a correction to Q of about 1 keV.

The $B^{10}(d,\alpha)Be^8$ reaction was that which provided the particle with $B\rho = 517$ kG cm with which the calibration curve shape was checked. All of the calibration points were each also a measurement of this Q value. No Po-α group was recorded, nor any other attempt at field calibration made in this series of calibration checks. The spectrograph field was of course varied, but input energy and reaction angle remained constant. These facts in addition to the fact that all of the runs were taken in "one sitting" caused us to consider these measurements as less than independent in the calculation of the standard deviation of the mean. Runs 1 through 6 were taken with Po-α calibrated field and varying input energies and reaction angles. Each of the field calibration runs (runs 7 through 19) was treated as one-third of a measurement, and assigned a weight factor of 0.33. The total number of runs was then taken to be 10.33.

Since all of the calibration shape check runs were taken with an uncalibrated field, their estimated random calibration error was 0.1%. If we were to disregard all of these runs, the difference in the Q value would be 0.1 keV; the effect on the standard deviation, however, would be more appreciable. If the runs were considered independent and simply weighted one-third, the standard deviation of the mean would be 0.75 keV instead of the adopted value of 1.0 keV.

The previously reported work[25] on the $Be^9(p,\alpha)Li^6$ reaction gave a Q value of 2125.4 keV as a weighted mean of 12 measurements. The standard deviation of the mean was 0.2 keV and the best estimate of error was 1.8 keV, with the largest systematic uncertainty coming from the group shape.

Both the $Be^9(p,d)Be^8$ reaction and the $Be^9(d,t)Be^8$ reaction were taken without field calibration, so calibration uncertainty was a large source of error. Since the assigned calibration uncertainties are taken to be precentages of the measured Q values, this effect is not too large for the low Q of the (p,d) reaction. In the (d,t) reaction however, the estimated systematic uncertainty is 2.3 keV. Also contributing to this rather large calibration error is the fact that the runs were taken at only three different field settings.

Comparison of Q-Value Results with Others

The results of this work are summarized in the last column of Table VIII. Two numbers are quoted after the measured Q value, the first is the standard deviation of the mean and the second is the best estimate of error. Other columns contain the results of other experimenters. Column eight, headed Mattauch *et al.*, contains the self-consistent Q values presented in the 1964 Mass Table.

The measured Q values listed in the table are corrected for change in calibration standard when necessary. With the exception of the work done at the University of Mexico, the Q values measured else-

TABLE VIII. Summary of measured Q values and comparison with previous results. Results from other laboratories have been adjusted for change in calibration energy, when necessary, based on Po^{210} alpha energy of 5304.5±0.5 keV. Two errors are given for each Q value measured in this work. The first is the standard deviation of the mean and the second is the best estimate of error from Table VII. Energy units are keV.

	MIT[a]	University of Mexico	California Inst. Tech.	Wisconsin	Birmingham	Others	Mattauch *et al.*[h]	This work
$D(d,p)T$	4034±6	4025±8[c]	4030 ±12[d]	4039.4±5[e]			4032.9±0.12	4033.7±0.3,1.7
$C^{12}(d,p)C^{13}$	2722±4	2719±10[f]			2720 ±2[g]	2722±4[h]	2722.3±0.8	2722.3±0.3,0.6
$D(He^3,p)He^4$		18380±10[c]					18353.5±0.4	18350.1±1.9,3.9
$B^{10}(He^3,p)C^{12}$							19694.5±0.6	19694.5±1.5,3.6
$Be^9(He^3,p)B^{11}$		10344±13[c]					10325.2±1.2	10322.1±1.2,2.3
$B^{11}(He^3,p)C^{13}$		13221±10[c]					13185.4±1.0	13185.4±0.9,4.0
$C^{12}(He^3,p)N^{14}$		4806±9[c]	4778.9±1.4[i]				4778.6±0.18	4776.3±0.4,1.5
$B^{11}(He^3,d)C^{12}$							10463.1±0.4	10469.7±1.6,5.7
$B^{11}(d,\alpha)Be^9$	8024±7	8035±9[c]			8029.0±5[g]		8028.3±1.2	8029.7±1.5,2.8
$B^{10}(d,\alpha)Be^8$		17830±6[c]			17829 ±10[g]		17819.1±1.3	17818.6±1.0,4.1
$Be^9(p,d)Be^8$	562±4	560±4[f]		557.5±2[j]	560 ±3[k]	558±5[l]	559.4±0.6	559.6±0.2,0.6
$Be^9(p,\alpha)Li^6$	2144±6	2119±8[f]	2117 ±7[d]	2123 ±4[j]	2126 ±3[k]	2130±10[l]	2126.4±1.2	2125.4±0.2,1.8
$Be^9(d,t)Be^8$	4602±13						4592.3±0.6	4591.7±0.3,3.1
$C^{13}(d,t)C^{12}$	1311±6	1311±6	1311.0±3[m]				1310.6±0.8	1310.9±0.3,0.7
$B^{10}(\alpha,p)C^{13}$	4068±12						4063.3±1.0	4063.4±1.3,2.4

[a] See Ref. 13.
[b] See Ref. 2.
[c] See Ref. 15.
[d] See Ref. 12.
[e] See Ref. 14.
[f] See Ref. 24.
[g] See Ref. 21.
[h] See Ref. 19.
[i] See Ref. 18.
[j] See Ref. 16.
[k] See Ref. 22.
[l] See Ref. 20.
[m] See Ref. 17.

where generally agree with those measured in this work to within stated errors. Exceptions are the MIT value for the $Be^9(p,\alpha)Li^6$ Q value and the measurement of the $C^{12}(He^3,p)N^{14}$ done by Bardin *et al.*[18] at the California Institute of Technology.

The difficulties encountered by the University of Mexico group have already been mentioned. The MIT measurement of the $Be^9(p,\alpha)Li^6$ Q value is 14 keV higher than the next highest reported measurement of this reaction. This measurement was performed as described previously using the annular magnet. Since the five other precision measurements of this Q value agree to within stated errors with the number obtained in this work, it is felt that the MIT value is high.

The Q value of the $C^{12}(He^3,p)N^{14}$ reaction listed in the California Institute of Technology column is actually a combination of a measurement of the Q value to the first excited state of N^{14} as made at Cal. Tech. and a measurement of the excitation energy of this state performed by Sanders[33] at Wisconsin. The excitation energy, corrected for change in the $Li^7(p,n)$ threshold,[34] is given as 2311.0±1.2 keV. The Q value to the excited state is given as 2467.9 ±1.0 keV, also corrected for change in energy standard. The sum of these two measurements gives a value for the ground state Q value of the $C^{12}(He^3,p)N^{14}$ reaction of 4778.9±1.5 keV. The difference between this value and that measured in this work is 2.6 keV, whereas the root-mean-square sum of the best estimate of error for this experiment and the error of 1.5 keV quoted for the Cal Tech measurement is 2.1 keV.

A preliminary report of the Cal Tech work[35] gave a value for the ground state Q of 4777.4±1.5 keV when corrected for energy standard; this value also depends on Sanders' value for the excitation energy. This number agrees rather well with that obtained in this work.

The energy of the de-excitation gamma ray from the 2.3-MeV state of N^{14} was recently measured[36] at Brookhaven National Laboratory. The excitation energy was found to be 2312.9±0.1 keV. This is an excitation energy 1.9 keV higher than that of Sanders and makes the discrepancy between our value and the Cal Tech value for the $C^{12}(He^3,p)N^{14}$ Q value still larger.

An accurate measurement of the $Be^9(p,d)Be^8$ Q value which was reported very recently[23] is not included in Table VIII. The reported value of 559.0±1.1 keV agrees beautifully with the results of the present measurement.

The agreement of the results of this work with the consistent set of Q values of Mattauch *et al.* is in general excellent. In ten of the fifteen measured Q's, the difference is less than the rms sum of Mattauch's error with the standard deviations of the means of the Q values measured in this work. For two other reactions, the rms sum of Mattauch's error and the best estimate of error given in this work is more than the difference. The three remaining reactions which have differences outside the stated errors are: $Be^9(He^3,p)B^{11}$ with a difference of 3.1 keV and a rms error of 2.4 keV (using the best estimate of error), $C^{12}(He^3,p)N^{14}$ with a difference of 2.3 keV and a rms error of 1.5 keV, and $B^{11}(He^3,d)C^{12}$ with a difference of 6.6 keV and a rms error of 5.7 keV. The agreement for the first reaction is fairly good. The mass table Q value for the second reaction is probably based almost entirely on the reaction energy as measured by Bardin *et al.*, which has

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[33] R. M. Sanders, Phys. Rev. **104**, 1434 (1956).

[34] J. B. Marion, Rev. Mod. Phys. **38**, 660 (1966).

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

[36] K. W. Jones (private communication).

been discussed previously. The large stated error in the third reaction reflects the difficulty of calibrating the spectrograph field at the extremely high fields needed to measure the deuteron energy. It is gratifying that these precise measurements do agree quite well with the numbers obtained with the statistical methods of Mattauch *et al.* from a mass of considerably less precise data.

The highest Q value measured, that of the $\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}$ reaction relates the same two nuclei as the recently measured $\mathrm{C^{12}}(d,\alpha)\mathrm{B^{10}}$ and $\mathrm{B^{10}}(\alpha,d)\mathrm{C^{12}}$ reactions. To compare the results one must of course assume values for the H, D, $\mathrm{He^3}$, and $\mathrm{He^4}$ masses. If the mean of the Q values found for the (α,d) reaction and its inverse is added to the mean of Q values given below for the $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ reaction the result is 19692.3±2.2 keV. This agrees very well with the value 19694.5±3.6 keV found here for the $\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}$ Q value.

Calculation of the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ Q Values Using Reaction Cycles

After the computation of the Q values was completed, reaction cycles were constructed which closed to 0, the $\mathrm{D}(d,p)\mathrm{T}$, or the $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ Q values. These cycles were independent in the sense that no one of them could be constructed from a sum or difference of any other cycle closing to the same Q value.

The cycles closing to zero are the following:

Cycle 1. $\mathrm{C^{12}}(d,p)\mathrm{C^{13}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(\mathrm{He^3},d)\mathrm{C^{12}}$

Cycle 2. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{12}}(d,p)\mathrm{C^{13}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$

Cycle 3. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{13}}(d,t)\mathrm{C^{12}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(d,t)\mathrm{Be^8}$

Cycle 4. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{B^{11}}(\mathrm{He^3},d)\mathrm{C^{12}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$. The closure errors of these cycles are as follows, where the first number quoted after the ± sign is the rms sum of the standard deviations of the mean of each of the reactions in the cycle, and the second number is the rms sum of the best estimates of error: 6.6±1.9, 7.0 keV; 2.1±2.6, 7.4 keV; 1.0±2.9, 7.0 keV; and 4.5±2.9, 8.4 keV.

The cycles closing to the $\mathrm{D}(d,p)\mathrm{T}$ Q value are the following:

Cycle 1. $\mathrm{C^{13}}(d,t)\mathrm{C^{12}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(\mathrm{He^3},d)\mathrm{C^{12}}$

Cycle 2. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{13}}(d,t)\mathrm{C^{12}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$

Cycle 3. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{12}}(d,\mathrm{He^3})\mathrm{B^{11}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(d,t)\mathrm{Be^8}$

Cycle 4. $\mathrm{C^{13}}(d,t)\mathrm{C^{12}}:\mathrm{C^{12}}(d,p)\mathrm{C^{13}}$

Cycle 5. $\mathrm{Be^9}(d,t)\mathrm{Be^8}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$

The cycles closing to the $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ Q value are the following:

Cycle 1. $\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{12}}(d,p)\mathrm{C^{13}}:\mathrm{C^{13}}(p,\alpha)\mathrm{B^{10}}$

Cycle 2. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\alpha,p)\mathrm{C^{13}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$

Cycle 3. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{13}}(d,t)\mathrm{C^{12}}:\mathrm{B^{11}}(\mathrm{He^3},p)\mathrm{C^{13}}:\mathrm{Be^9}(\mathrm{He^3},p)\mathrm{B^{11}}:\mathrm{Be^9}(d,t)\mathrm{Be^8}$

Cycle 4. $\mathrm{B^{10}}(d,\alpha)\mathrm{Be^8}:\mathrm{B^{10}}(\mathrm{He^3},p)\mathrm{C^{12}}:\mathrm{C^{12}}(d,\mathrm{He^3})\mathrm{B^{11}}:\mathrm{Be^9}(\mathrm{He^3},p)\mathrm{B^{11}}:\mathrm{Be^9}(p,d)\mathrm{Be^8}$

Cycle 5. $\mathrm{Be^9}(\mathrm{He^3},p)\mathrm{B^{11}}:\mathrm{B^{11}}(d,\alpha)\mathrm{Be^9}$.

Tables IX and X present the values of the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ Q value obtained for each cycle; the rms sum of the standard deviations, and the best

TABLE IX. Values of the $\mathrm{D}(d,p)\mathrm{T}$ Q value as obtained from reaction cycles and from the direct measurements. Energy units are keV.

Cycle	Q	σ[a]	Best estimate of error[b]	Consistency factor[c]
1	4026.6	2.0	7.0	
2	4031.1	2.5	7.4	
3	4027.6	3.3	8.9	
4	4033.2	0.4	0.9	
5	4032.1	0.37	3.1	
Direct measurement	4033.7	0.3	1.7	
Weighted mean	4033.0[d]			
Standard deviation, σ_m	0.44[d]			
Internal error using σ		0.20		
Internal error using best estimate of error			0.67	
Consistency factor using internal error based on σ				2.2
Consistency factor using internal error based on best estimate of error				0.66
Theoretical consistency factor[e]				1.0±0.29

[a] Cycle closure error calculated using the standard deviation of the mean of each reaction in the cycle.

[b] Cycle closure error calculated using the best estimate of error for each reaction.

[c] Consistency factor $=\sigma_m$/internal error. See Ref. 37.

[d] Weighting factors given by $w_i=1/\sigma^2$.

[e] Theoretical consistency factor $=1.0\pm1/(2f)^{1/2}$. See Ref. 37.

TABLE X. Values of the $\mathrm{D}(\mathrm{He^3},p)\mathrm{He^4}$ Q value as obtained from reaction cycles and from the direct measurement. Energy units are keV.

Cycle	Q	σ	Best estimate of error	Consistency factor
1	18353.4	2.1	4.4	
2	18351.3	2.4	6.3	
3	18350.8	2.4	7.4	
4	18356.3	2.7	8.2	
5	18351.8	1.6	3.5	
Direct measurement	18350.1	1.9	3.9	
Weighted mean	18352.0			
Standard deviation, σ_m	0.80			
Internal error, using σ		0.86		
Internal error, using best estimate of error			2.0	
Consistency factor using internal error based on σ				0.93
Consistency factor using error based on best estimate of error				0.40
Theoretical consistency factor				1.0±0.29

estimates of error of each of the reactions making up the cycle. These Q values are weighted inversely as the square of the standard deviations, and a mean value obtained. The standard deviation of the mean is also computed. This standard deviation of the mean value of the Q's as calculated from the reaction cycles is called the external error. This value is the one used in any further computations.

Since each of the cycles provides us with an independent (to a greater or lesser degree) measurement of the Q value, a check on the internal consistency of the measurements may be made. An internal error is computed using for the ΔE's the standard deviations, σ, of each of the cycles. Another internal error is also calculated using ΔE's equal to the cycle error based on the best estimates of error. These values are also given in Tables IX and X. The ratio of the external error to the internal error is called the consistency factor. This factor is given for the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He}^3,p)\mathrm{He}^4$ Q values in Tables IX and X, respectively. For each reaction it is calculated using the internal error based both on standard deviations and on best estimates of error.

According to Birge[37] and Mattauch,[38] for a truly normal distribution of errors, the consistency factor should differ from unity only by statistical fluctuations. The expected value of the consistency factor is given by the formula

$$\sigma/e_{\mathrm{int}}=1\pm1/(2f)^{1/2},$$

where f is the number of elements in the sample; here f is 5. If f is a large number, the probability that the value obtained for the consistency factor will lie within the limits given by this expression is 0.68. If the value of the consistency factor is larger than one by an amount several times the expected deviation, errors assigned to the original Q values are too small. If these errors are standard deviations, this implies that systematic errors are present.

If the value of the consistency factor is, within statistical variations, unity, Birge[37] states that we may choose either the internal error or the external error (the standard deviation of the mean) as the error to be quoted with the mean of the observations in question. We may then think of the internal error as a prediction of what the resultant external error will be, if all is well and errors are randomly distributed.

For the $\mathrm{D}(d,p)\mathrm{T}$ Q value, the consistency factor calculated from the best estimates of error is less than one, whereas that based on standard deviations is about 3 times the expected statistical deviation. For the $\mathrm{D}(\mathrm{He}^3,p)\mathrm{He}^4$ data the consistency factor is less than one regardless of which definition of error is used to calculate it. For the cycles mentioned above which close to 0, the two consistency factors are 1.5 and 0.76 based on σ and best error, respectively, while the expected deviation is ±0.35.

The general conclusion drawn from these consistency factors is that the standard deviations are a bit too optimistic and the best estimates of error are a bit too conservative. In the calculation of the masses to follow, the mean values for the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He}^3,p)\mathrm{He}^4$ Q values obtained from the cycles and the direct reaction measurements are used. The errors assigned to these values are taken to be the external errors, in concordance with Birge.

Calculation of the Mass Excesses of T, He^3, and He^4 and Comparison with Other Work

The reaction cycles yielded no other independent relations between the five reaction particles, so in order to obtain the mass excesses of the T, He^3, and He^4 atoms, we were forced to assume values for the mass excesses of the H and D atoms and also the mass difference between the triton and the He^3 particle. As mentioned earlier the agreement between various experimenters is excellent for these values and all agree well with the mass table. For the purpose of the comparison of this work with others, however, these "known" masses (H, D, and T-He^3) were taken as much as possible from the work of the laboratory with which the comparison was made. These comparisons are presented in Table XI. The sections headed Brookhaven, Harvard, Demirkhanov *et al.*, Minnesota, Mattauch and Bieri, and Ogata and Matsuda contain results obtained from mass-spectrographic analysis. The section headed Wapstra contains masses obtained from nuclear reaction data only. The section headed Mattauch *et al.* gives the masses found in the 1964 Mass Table. The errors appearing after the masses, as calculated from the Q values measured in this work are the rms sums of the errors attributed to the H and D masses and the T-He^3 mass difference by the appropriate authors and the external errors of the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He}^3,p)\mathrm{He}^4$ measurements appearing in Tables IX and X.

The agreement evidenced in Table XI is quite good for the triton and He^3 masses, but discrepancies outside stated errors occur for the He^4 mass, particularly for some of the mass spectroscopic data. The latest value of the He^4 mass is taken from the D_2-He^4 mass doublet measurement of Benson *et al.*[39] Using the H and D masses measured at the same laboratory by Quisenberry *et al.*[10] to calculate the He^4 mass from the doublet and from the Q values of this work, we find almost perfect agreement. The agreement between the mass table value for the He^4 and our value is also rather good. The evaluation of the $\mathrm{D}(d,p)\mathrm{T}$ and $\mathrm{D}(\mathrm{He}^3,p)\mathrm{He}^4$ Q values as done in this work provides the best measure-

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[37] R. T. Birge, Phys. Rev. **40**, 207 (1932).

[38] J. Mattauch, in *Proceedings of the Conference on Nuclidic Masses*, edited by H. E. Duckworth (University of Toronto Press, Toronto, 1960), p. 3.

[39] J. L. Benson, R. A. Damerow, and R. R. Ries, Phys. Rev. **113**, 1105 (1959).

TABLE XI. Mass excesses of T, He^3, and He^4 as calculated from the Q-value data of this work compared with those from other laboratories. To facilitate comparison, the H and D masses and the T-He^3 mass difference used to calculate the T, He^3, and He^4 masses are taken from those measured at the appropriate laboratories. Units are μu.

	Brookhaven[a]	This work[b]	Harvard[c]	This work[d]
T	16048.19 ±0.38	16049.0 ±0.49	16050.74 ±0.79	16050.3 ±0.57
He^3	16028.15 ±0.22	16029.0 ±0.53	16030.98 ±0.54	16030.5 ±0.60
He^4	2599.65 ±0.31	2603.9 ±1.0		
	Demirkhanov *et al.*[e]	This work[f]	Minnesota[g]	This work[h]
He^3	16011 ±2	16020 ±2.3		
He^4	2600 ±2.7	2592 ±2.5	2601.3 ±0.7	2601.5 ±1.3
	Mattauch and Bieri[i]	This work[j]	Ogata and Matsuda[k]	This work[l]
He^4	2607.2 ±1.1	2609.5 ±1.4	2606 ±1.3	2601 ±3.6
	Wapstra[m] (from Q values)	This work[n]	Mattauch *et al.*[o] (Mass table)	This work[p]
T	16046 ±5	16045 ±3.2	16049.71 ±0.21	16049.5 ±0.49
He^3	16027 ±5	16025 ±3.2	16029.73 ±0.21	16029.5 ±0.49
He^4	2601.4 ±1.7	2598.6 ±3.3	2603.12 ±0.42	2604.5 ±0.99

[a] Smith and Friedman and Smith (Refs. 4, 3).
[b] Uses the H and D masses and the T-He^3 mass difference of Smith and Friedman and Smith (Refs. 4, 3).
[c] Moreland and Bainbridge (Ref. 5).
[d] Uses the H mass of Mattauch *et al.* (Ref. 1). D mass and T-He^3 mass differences are from Moreland and Bainbridge (Ref. 5).
[e] Demirkhanov *et al.* (Ref. 6).
[f] Uses the H and D masses of Demirkhanov *et al.* (Ref. 6) and the T-He^3 mass difference of Mattauch *et al.* (Ref. 1).
[g] From Benson *et al.*'s value for the D_2-He^4 doublet and the D and H masses of Quisenberry *et al.* (Refs. 39, 10).
[h] Uses H and D masses of Quisenberry *et al.* (Ref. 10). T-He^3 mass difference of Mattauch *et al.* (Ref. 1).
[i] See Ref. 11.
[j] Uses H and D masses of Mattauch and Bieri (Ref. 11) and the T-He^3 mass difference of Mattauch *et al.* (Ref. 1).
[k] See Ref. 9.
[l] Uses H and D masses of Ogata and Matsuda (Ref. 9) and the T-He^3 mass difference of Mattauch *et al.* (Ref. 1).
[m] See Ref. 43.
[n] Uses H and D masses of Wapstra (Ref. 43) and the T-He^3 mass difference of Mattauch *et al.* (Ref. 1).
[o] See Ref. 1.
[p] Uses H and D masses and T-He^3 mass difference of Mattauch *et al.* (Ref. 1).

ment to date, based on reaction data, of the T, He^3, and He^4 mass excesses.

Calculation of the Mass Excesses of Li^6, Be^8, Be^9, B^{10}, B^{11}, C^{13}, and N^{14} and Comparison with Other Results

Using the H, D, and T-He^3 mass difference obtained from the 1964 Mass Table of Mattauch *et al.* and the Q values measured in this work, the mass excesses of the above listed nuclides were calculated. Since all of the nuclides except Li^6 and N^{14} are determined by two or more Q values, a process similar to that used with the cycles was employed. A mass excess was calculated from each of the applicable Q values. An error was also calculated for each of these values. This error was the rms sum of the standard deviation of the Q value and the errors attached to the other masses involved in the reaction. For the H and D masses the errors used were those supplied in the mass table. For He^3, T, and He^4, the mass values and the errors used were those calculated from the Q values measured here and the mass table values of the H and D masses and the T-He^3 mass difference. These masses, along with their errors appear in Table XI under the heading Mattauch *et al.*

Using these errors, a weighted mean of the various values of the mass excess was calculated. Two internal errors, one based on the rms standard deviations and the other based on the rms best errors of the Q values, were calculated. The external error, σ_m, of the mean of the two or three measurements was also calculated. In only one case, that for the B^{11} mass, was this external error larger than the internal error calculated on the basis of the standard deviations, and in no case was the external error larger than the internal error calculated from the best estimates of error.

The weighted mean values of the mass excess along with the internal errors based on the standard deviations and on the best estimates of error are presented in Table XII. For the B^{11} case, the external error of the mean obtained from the two Q values and the internal error based on the best error estimates are presented.

Table XII shows the results of the mass measurements made in this work, the results of mass spectroscopic measurements,[4,8,9,40,41] and the results obtained from the mass table. A comparison with the masses based solely on Q values as compiled by Li *et al.*[42] or Wapstra[43] was not made because of the difficulty of correcting these values for changes in energy standards.

Agreement with mass spectroscopic results is not striking; however, in all cases except the N^{14} mass, the discrepancies in the mass spectroscopic data themselves are comparable to the difference between mass spectroscopic data and the masses obtained in this work.

Agreement between the mass table and this work is excellent. The masses agree to within the stated errors based on the standard deviations in all cases except that of N^{14}. This discrepancy is not surprising because it is just the reappearance of the difference between the Cal Tech measurement of the $C^{12}(He^3,p)N^{14}$ Q value and our own in a different guise. The mass-spectroscopic data also are consistent in suggesting the lower value for the mass excess of N^{14}. The values listed in Table XII constitute the best systematic measurement of these mass excesses by nuclear reaction methods.

SUMMARY

The conclusions that may be drawn from this work are as follows: With careful attention to experimental detail, the errors present in Q-value measurements may be reduced by a factor of about 5 from those generally reported previously. The values obtained for the consistency factors indicate that the real unknown and unknowable error present in these measurements is generally between the quoted standard deviations and the best estimates of error. By virtue of the procedure of making large numbers of observations on each of the

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[40] K. Ogata and S. Matsumoto, in *Nuclidic Masses*, edited by W. H. Johnson (Springer-Verlag, New York, 1964), p. 415.

[41] T. T. Scolman, K. S. Quisenberry, and A. O. Nier, Phys. Rev. **102**, 1076 (1956).

[42] C. W. Li, W. Whaling, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **83**, 512 (1951).

[43] A. H. Wapstra, Physica **21**, 367 (1955).

TABLE XII. Comparison with other values of the mass excesses of Li^6, Be^8, Be^9, B^{10}, B^{11}, C^{13}, and N^{14} as calculated from the Q-value data of this work. The mass excesses of H and D and the T-He^3 mass difference used in the calculation are taken from the mass tables of Mattauch *et al.* These masses and the $D(d,p)T$, $D(He^3,p)He^4$ Q value data are used to obtain the T, He^3, and He^4 masses used in the calculation. Units are μu.

	Li^6	Be^8	Be^9	B^{10}	B^{11}	C^{13}	N^{14}
Smith[a]				12940.5±0.31	9306.29±0.10		3074.698±0.034
Osaka				12923 ±8[b]	9311 ±6.6[b]	3371 ±5.5[b]	3072.6 ±2.2[c]
Minnesota[d]				12944 ±3.2	9309.9 ±5.1	3358.9±0.4	3074.4 ±0.3
Ewalde[e]						3404 ±7	3073 ±6
Mass table[f]	15124.7±1.2	5307.9±0.9	12185.5±1.0	12938.8±0.5	9305.30±0.32	3354.4±0.9	3074.39 ±0.17
This work	15123.7[g]	5307.3[h]	12184.8[i]	12938.2[i]	9307.6[i]	3354.5[i]	3076.6[g]
Error based on σ_m	1.5[j]	0.79[i]	1.1[j]	1.2[j]	3.1[k]	0.31[i]	0.67[j]
Error based on best estimate of error[l]	3.8	2.3	3.2	2.3	3.5	0.54	1.7

[a] See Ref. 4.

[b] See Ref. 9.

[c] See Ref. 40.

[d] See Ref. 41.

[e] See Ref. 8.

[f] See Ref. 1.

[g] Calculated from one Q-value measurement.

[h] Calculated from three independent Q-value measurements.

[i] Calculated from two independent Q-value measurements.

[j] With the exception of B^{11}, the consistency factor, σ/internal error, is within statistical fluctuations of 1; therefore, internal error was chosen.

[k] The calculation of the standard deviation of the mean, σ_m, of the two measurements yielded a consistency factor of about 10. Therefore, the σ_m was chosen.

[l] Consistency factors here were all less than 1; therefore, internal error was chosen.

Q values to be measured, it appears that most of the errors have been randomized.

The rather unorthodox procedure of quoting two errors is felt to contain more meaning than simply quoting either standard deviations or limits of error. In general it is felt that the best estimate of error is a realistic, though perhaps (by virtue of the values of the consistency factors obtained) slightly conservative estimate of the accuracy of the experiment.

It is felt that development of the spectrograph field cycling procedure has improved the knowledge of the spectrograph field to the extent that the rather tedious procedure of calibrating each field against a freshly made Po-α source may be eliminated in all but the most precise measurements without the loss of much accuracy. The cycling procedure appears to reduct the calibration uncertainty to around 0.03% in energy.

Previous determinations of the T, He^3, and He^4 mass excess by mass spectroscopists have differed from one another by amounts several times the stated error. The errors quoted in this work are smaller than the discrepancies between the previous results. It is felt that the masses of the nuclides He^3, T, He^4, Li^6, Be^8, Be^9, B^{10}, B^{11}, C^{13}, and N^{14} as measured in this work constitute the most accurate measurement of these masses by Q-value techniques, and for the masses of Li^6 through C^{13} the most accurate measurement by any method.

A Q value of over 19.5 MeV was measured with an accuracy of 0.018% and the energy of particles with magnetic rigidity of 517 kG cm was measured with comparable accuracy. Thus, particle energies 4 times that of Po-α, known to no worse than twice the uncertainty of the latter, may be produced for use as a secondary energy standard.