Accelerator Calibration Energies*

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The absolute measurements of nuclear reaction energies appropriate for calibration purposes are critically reviewed and recommended values are given. A sufficent number of points are now known with precision to permit the calibration of proton beams up to 60 MeV.

I. INTRODUCTION

Because only a few accelerators are, at the present time, equipped with absolute instruments for measuring the beam energy, most nuclear reaction experiments are performed with energy analyzers that require calibration. As techniques become more sophisticated, it is increasingly necessary that calibration points of high precision be available. The status of accurately known resonance and threshold energies that are suitable for calibration purposes was reviewed in 1961 (Ma 61) and again in 1963 (Ma 64). Since the last report, the situation has improved sufficiently to warrant a new survey and to list a new set of recommended calibration energies. A more critical evaluation of the data is attempted in this report than was felt appropriate in the past.

Measurements of 16 different reaction energies have been considered and weighted averages are given (see the tables below). These energies cover the range up to $E \cong 10$ MeV with reasonable uniformity. In addition, calculated energies (based on the most recent adjustment of atomic masses) are given for several nuclear reactions which will permit the calibration of magnetic beam analyzers for proton energies up to 60 MeV.

II. SELECTION OF DATA

In recent years, experimenters have become increasingly aware of the subtleties involved in performing precision measurements of nuclear reaction energies. Indeed, most of the work reported in the past few years is characterized by careful attention to minute details of procedure. These recent measurements with improved, modern equipment have yielded several results with a precision approaching (and even exceeding) 1 part in 10^4. The older measurements are generally of lower precision and in some cases were made without proper regard for effects that are now known to be important. The correction of these older measurements to conform to currently accepted practice is at best difficult (and often impossible) to perform with reliability. In view of these facts, it was decided to include only recent measurements (post-1958) in determining recommended values of reaction energies. (1958, the date of the first publication of the initial measurements with the 2-m electrostatic analyzer at the U. S. Naval Research Laboratory, marks the beginning of the current generation of precision energy measurements.) Some discussion of the omitted measurements is given in the appropriate sections below.

In addition to the omission of pre-1958 results, the energy measurements made in 1959–60 with the electrostatic analyzer at Associated Electrical Industries, Aldermaston, England, have also been deleted from the analysis. The reason is an apparent systematic error in the AEI results. Whereas the weighted mean value of all other results for the $Al^{27}(p, \gamma)Si^{28}$ resonance energy is 991.90±0.04 keV, the AEI value is 994.0±1.0 keV; similarly, for the $F^{19}(p, \alpha\gamma)O^{16}$ resonance, the weighted mean is 872.11±0.20 keV compared to 873.9±0.8 keV measured at AEI (Hu 60). The deviation in each case is about 0.2%, twice the stated uncertainty and about ten times the standard deviation in the weighted mean of all the other measurements. At the lower energy $F^{19}(p, \alpha\gamma)O^{16}$ resonance, the AEI value is also high (340.9±0.3 keV compared to 340.46 keV for the mean), but only by 0.13%. Thus, the AEI results appear to be systematically high by about 0.2%, an intolerably large discrepancy in view of the precision of (and close agreement among) the other measurements.

Having eliminated the pre-1958 and the AEI measurements, we further restrict the set of input data by choosing only *absolute* measurements (electrostatic, magnetic, or velocity). We relax this requirement slightly to allow also the inclusion of results obtained by the direct comparison of beam energy with the energy (measured absolutely) of α particles from such sources as Po^{210}, ThC, and ThC′, since these energies are now known with considerable precision (Wa 64). By considering only absolute measurements, a large number of *relative* energy measurements are excluded. Such measurements, which frequently are based on more than one calibration point, are difficult to adjust for changes in calibration energies. Furthermore, if the measured energy is far removed from the calibration energy [for example, basing an energy for the $N^{14}(p, n)O^{14}$ threshold at 6.36 MeV on the $C^{13}(p, n)N^{13}$ threshold energy at 3.236 MeV], the result depends heavily on the linearity of the beam energy analyzer

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(which usually is not—or cannot be—demonstrated). However, in the list of nuclear reactions chosen for this survey, the number of relative energy measurements that could otherwise have been included is rather small. [Only in the cases of the $F^{19}(p, n)Ne^{19}$ and $Al^{27}(p, n)Si^{27}$ reactions have a significant number of relative measurements been excluded.] Fortunately, a sufficiently large number of absolute experiments has been performed that it is no longer necessary to rely on the less precise relative measurements.

III. CORRECTION OF DATA

Alterations of some published energy values used in this survey have been made for two reasons: (1) errors in computation or in analysis technique, and (2) adjustments necessitated by changes in the recommended values of the fundamental constants that enter the calculation. The latter are easily made by substituting the latest values (Co 65) for the ones used in the original calculations. Into this category fall the following:

(a) Gasten's measurements (Ga 63) of the $Li^7(p, n)Be^7$ threshold energy and the $Al^{27}(p, \gamma)Si^{28}$ resonance energy have been increased by 39 parts per million (ppm) because of the change in the proton mass from 938.219 MeV to 938.256 MeV. This correction amounts to +0.07 keV and +0.04 keV in the two energies.

(b) The $F^{19}(p, \alpha\gamma)O^{16}$ resonance energy of Seagrave *et al.* (Se 64) has also been corrected (by +26 ppm) for a change in m_pc^2.

(c) The Rice measurements (Be 61, Bo 66) have been corrected for a decrease of 41 ppm in the value of the gyromagnetic ratio of the proton and for a decrease of 48 ppm in the value of e/m for the proton. These quantities enter as $(e/m)/\gamma_p^2$, so the net effect is to increase the stated energies by 34 ppm.

Changes in the least-squares-adjusted values of the fundamental constants since the time of publication cause changes in all of the other energy values that are negligibly small (a few eV at most).

Only one case of a correction of type (1) has been made:

(a) In Gasten's report (Ga 63) of his velocity measurements, the various contributions to the uncertainties in the results are tabulated. For the $Al^{27}(p, \gamma)Si^{28}$ resonance energy and the $Li^7(p, n)Be^7$ threshold energy, the rms errors are 20 and 32, respectively, in units of $\%E\times10^{-3}$. These are *relative* errors, but they have apparently been applied as *absolute* errors; this results in no change for the uncertainty in the $Al^{27}(p, \gamma)Si^{28}$ value (±0.2 keV), but the listed error for the $Li^7(p, n)Be^7$ threshold energy (±0.3 keV) should properly be ±0.6 keV. The latter error is shown in Table II and has been used in the calculation of the weighted mean threshold energy.

IV. TREATMENT OF DATA

In order to compute a weighted mean value for each of the energy points selected, it is necessary to decide whether the rules of standard statistical analysis apply. For a statistical sample, the weighting factor for the ith measurement is

$$\text{weighting factor} = w_i = (\Delta E_i)^{-2}, \tag{1}$$

where ΔE_i is the stated uncertainty in the ith value. This procedure is valid: (a) if all of the uncertainties have been assigned in a uniform manner (e.g., standard deviations), and (b) if a sufficient number of measurements has been made to constitute a "statistical sample." In the previous surveys (Ma 61, Ma 63), it was argued that neither of these criteria is met and therefore that an arbitrary weighting procedure is perhaps more reasonable than that dictated for truly statistical cases; it was decided to assign weights according to $w_i = (\Delta E_i)^{-1}$ as a compromise between *no* weighting and the severe *statistical* weighting.

Although several new measurements have been made since the last survey, the older measurements have now been excluded so that there is actually no significant increase in the number of input data; that is, we are no nearer to a "statistical sample" now than before. However, the recent measurements all appear to have been analyzed rather uniformly (see some specific comments below) so that the first objection to statistical weighting has now been met to an acceptable degree. This latter fact seems crucial and for the purposes of this survey outweighs the paucity of data. Therefore, standard statistical methods have been used in this analysis. That is, the weighting factors have been computed according to Eq. (1) and the *internal* and *external* errors are given by

$$e_{\text{int}}^2 = \Sigma w_i^2 (\Delta E_i)^2 / (\Sigma w_i)^2$$
$$= (\Sigma w_i)^{-1} \tag{2}$$

and

$$e_{\text{ext}}^2 = (N-1)^{-1} (\Sigma w_i \delta_i^2)(\Sigma w_i)^{-1}, \tag{3}$$

where $\delta_i = E_i - \bar{E}$ is the deviation of the ith value from the weighted mean. (*Standard deviations* rather than *probable errors* have been used throughout.)

The recommended value in each case is assigned an uncertainty equal to the *larger* of e_{int} or e_{ext}.

Fortunately, all of the experimenters who, in the recent past, have been engaged in precision energy measurements have followed the practice of listing all known contributions to uncertainties in their results and of calculating the rms error (in all cases, presumably the standard deviation). In the Rice experiments (Be 61, Bo 66), the rms error was given but a somewhat larger uncertainty was arbitrarily assigned to each result. This practice is not to be encouraged. After the most careful possible assessment of the experimental conditions and the estimation of the contributing uncertainties, the rms error is the most meaningful representation of the reliability of the data; to assign an additional "safety factor" unnecessarily distorts the results when viewed in the total context of all similar measurements. [For an amplification of this point, see Cohen and DuMond (Co 65, Sec. 1.4).] Therefore, in calculating the weighted mean values, the results of Beckner *et al.* (Be 61), and Bonner *et al.* (Bo 66) have been given weights inversely proportional to the squares of the rms errors, before the introduction of the "safety factor."

The results for resonance widths Γ have been treated in the same manner as the energy values.

V. ENERGY STANDARDS VERSUS THE "TRUTH"

This analysis of precision energy measurements aims to provide a recommended set of energy values that can be used for calibration purposes under normal laboratory conditions. Thus, if a well-defined procedure leads to a convenient method for the reproducible extraction of a number which we call, for example, the "neutron threshold" for a reaction, this is (by definition) a *calibration point;* it matters not at all whether the number so defined is the "true" neutron threshold in the sense that the Q value for the reaction can be accurately obtained therefrom.

For several years it has been recognized that the discrete nature of the energy loss process for ions traversing matter can influence the shape and the position of resonance and threshold yield curves. This Lewis effect (Le 62) has been incorporated into the analysis of the yield curves for (p, γ) resonances (see, e.g., Wa 62 and Bo 63) and for (p, n) thresholds (Be 64, Pa 66). These experiments and calculations have shown that the difference between the apparent resonance or threshold position and the "true" position can amount to 100–200 eV. Since we are not concerned here with precision measurements of Q values or energy level positions, these differences are not important—*if* it is possible to establish a standard procedure for defining the "calibration energy."

The procedure for determining a neutron threshold energy is dictated by the fact that the yield of s-wave neutrons from a thick target varies as the $\frac{3}{2}$ power of the neutron energy, i.e., approximately as $(\Delta E)^{\frac{3}{2}}$, where ΔE is the difference between the bombarding energy and the threshold energy. [This is not strictly true for the $Li^7(p, n)Be^7$ reaction in which a strong resonance occurs near threshold. However, the modification of the $(\Delta E)^{\frac{3}{2}}$ yield expression is not great.] Thus, a plot of $(\text{yield})^{\frac{2}{3}}$ versus bombarding energy can be extrapolated linearly to zero yield to determine the threshold energy. The effects on the extrapolated intercepts due to finite beam energy resolution and to discrete energy loss have been extensively investigated by Bondelid and Whiting (Bo 64) and by Palmer *et al.* (Pa 66). The mutual conclusion of these groups is that the extrapolated $(\text{yield})^{\frac{2}{3}}$ intercept lies 100–200 eV *below* the true threshold, the exact value depending on the beam energy resolution. However, for high resolution beams as are generally employed in present-day experiments (i.e., $E/\Delta E \approx 0.01-0.03\%$). The extrapolation of $(\text{yield})^{\frac{2}{3}}$ gives an intercept that is defined and reproducible to within about 100 eV. Therefore, since all of the results used here were obtained from measurements with high resolution beams, the intercept of the linear extrapolation of $(\text{yield})^{\frac{2}{3}}$ serves adequately to define the neutron threshold calibration points. It would be preferable to have a collection of absolute measurements with beams of known resolution and with the analysis performed in the manner of Bondelid and Whiting (Bo 64) or Palmer *et al.* (Pa 66); all presently known effects would then be taken into account. Tables are even available to expedite this procedure for the $Li^7(p, n)Be^7$ threshold (Pa 66). At present, the only absolute measurements that have been so analyzed are those of Bondelid and Whiting (Bo 64). Furthermore, such a procedure is usually more time-consuming than is warranted for most calibration purposes. Therefore, the $(\text{yield})^{\frac{2}{3}}$ extrapolation procedure seems sufficiently accurate for all but the most demanding present-day situations.

Similar comments apply for reasonance reactions. The familiar arctangent thick-target yield curve is modified by the discrete energy loss effect and an overshoot occurs at the peak of the curve (the Lewis effect). If the energy loss process were continuous rather than discrete, the midpoint of the arctangent curve would be the resonance position. The point at which the yield has risen to one-half of the constant yield at bombarding energies above the Lewis effect hump corresponds closely to the resonance energy. The displacement amounts to about 100 eV for the $Al^{27}(p, \gamma)Si^{28}$ resonance when a pure aluminum target is used. If the surface is partially oxidized, the displacement and the height of the Lewis effect hump are greatly reduced. Indeed, with partially oxidized targets as are commonly used for calibration purposes, there may actually be no displacement at all (Bo 63). In any event, if high resolution beams are employed, the half-maximum-yield point is defined and reproducible to within about 100 eV. Again, the procedure that neglects the Lewis effect is quite adequate for calibration purposes.

VI. LOW-ENERGY CALIBRATION POINTS

The vast majority of precision measurements of nuclear reaction energies have been made for bombarding energies below 3.5 MeV. Traditionally, the $Al^{27}(p, \gamma)Si^{28}$ resonance near 992 keV and the $Li^7(p, n)Be^7$ threshold near 1881 keV have served as the main calibration points for low-energy electrostatic accelerators. Since the deterioration of carbon targets is less severe than for aluminum or lithium targets, it has been suggested (Ph 64) that the $C^{13}(p, \gamma)N^{14}$ resonance near 1747 keV and the $C^{13}(p, n)N^{13}$ threshold near 3236 keV be adopted as the primary calibration points. Although there is much merit in this proposal, there is not a sufficient number of absolute measurements of these energies available at present to offer a precision comparable with the aluminum and lithium points. These latter points will probably be the best established markers on the nuclear energy scale for some time to come.

A. $Al^{27}(p, \gamma)Si^{28}$

The five values of the $Al^{27}(p, \gamma)Si^{28}$ resonance energy that have been reported in the post-1958 period are shown in Table I. Several of the values have been corrected as explained in the preceding sections. All of the energies (except the one from Bo 63) were determined by taking the midpoint of the thick-target yield curve. The value listed for the Bondelid and Butler experiment (Bo 63) requires some comment. The first publication of a result for the $Al^{27}(p, \gamma)Si^{28}$ resonance energy by the NRL group was in 1959 when 992.4±0.5 keV was obtained (Bo 59). The experiment was repeated the following year with the result E_R= 992.0 keV (Bo 60a), which value, as pointed out in Bo 63, was rounded up from 991.95 keV. The data of Bo 60a were re-analyzed in Bo 63 and the same result, 991.95 keV, was obtained because the effects of surface impurity happened to exactly cancel the slight decrease of the resonance energy brought about by the discrete energy loss effect. This value was then averaged with six other results from similar analyses of new measurements with different targets; the unweighted mean was 991.91±0.30 keV. Although this number refers to the *true* resonance energy rather than the midpoint of the rise, the discussion above clearly indicates that this difference can be at most a few tens of eV. Therefore, there seemed no point in attempting to adjust this value, especially in view of the fact that this result contributes only 4% to the weighted mean.

In addition to the AEI result, one older measurement has been omitted from the list, viz., 993.3±1.0 keV by Herb *et al.* (He 49). Although this experiment provided a valuable service in that an absolute nuclear energy scale was established for the first time, it probably suffered from excessive surface contamination of the target (high vacuum practice was not nearly the advanced art that it is today) which caused the resonance energy to be considerably higher than the value now accepted.

TABLE I. $Al^{27}(p, \gamma)Si^{28}$ resonance energies.

E_R(keV)	Γ(keV)	Method	Reference
	0.1 ±0.05		Bo 59
992.23 ±0.27[a]		Absolute magnetic	Be 61
991.83 ±0.10[b]	0.10±0.02[b]	Absolute magnetic	Ry 62
991.91 ±0.30[b]		Absolute electrostatic	Bo 63
991.64 ±0.2[c]		Absolute velocity	Ga 63
991.912±0.043		Absolute velocity	Ro 66
	0.090±0.035		Fe 66

Weighted mean: E_R=991.90 keV

e_{int}=0.04 keV

e_{ext}=0.04 keV

Recommended: E_R=991.90±0.04 keV; Γ=0.10±0.02 keV

[a] Corrected (from 992.2±0.5) as explained in the text.
[b] Supercedes an earlier published value.
[c] Corrected (from 991.6±0.2) as explained in the text.

TABLE II. $Li^7(p, n)Be^7$ threshold energies.

E_{th}(keV)	Method	Reference
1880.56 ±0.55[a]	Absolute magnetic	Be 61
1880.48 ±0.25[b]	Absolute magnetic	Ry 61a
1879.87 ±0.6[c]	Absolute velocity	Ga 63
1881.11 ±0.94[b]	Absolute electrostatic	Bo 64
1880.8 ±0.7[b]	Magnetic; comparison of E_{th} with Po α energy	Br 64 Wa 65
1880.617±0.078	Absolute velocity	Ro 66

Weighted mean: E_{th}=1880.60 keV

e_{int}=0.07 keV

e_{ext}=0.05 keV

Recommended: E_{th}=1880.60±0.07 keV

[a] Corrected (from 1880.5±0.8) as explained in the text.
[b] Supercedes an earlier published value.
[c] Corrected (from 1879.8±0.3) as explained in the text.

B. $Li^7(p, n)Be^7$

The six recent determinations of the threshold energy for the $Li^7(p, n)Be^7$ reaction are shown in Table II. Generally, the values are derived from the extrapolation of $(\text{yield})^{\frac{2}{3}}$, as discussed in Sec. V; the exceptions are as follows: The figure in the report by Beckner *et al.* (Be 61) which shows a typical yield curve for the $Li^7(p, n)Be^7$ reaction is *linear* in the yield. However, these authors state that $(\text{yield})^{\frac{2}{3}}$ extrapolations were also made and that no difference in the values was found. This result is probably due to the fact that the

Table III. $F^{19}(p, \alpha\gamma)O^{16}$ resonance energies.

E_R(keV)	Γ(keV)	Method	Reference
340.5 ±0.3	2.4±0.2	Absolute electrostatic	Bo 59
340.6 ±0.5[a]		Absolute magnetic	St 60
340.46±0.04[b]	2.4	Absolute velocity	Se 64

Weighted mean: E_R=340.45 keV

e_{int}=0.04 keV

e_{ext}=0.01 keV

Recommended: E_R=340.46±0.04 keV; Γ=2.4±0.2 keV

[a] Supercedes an earlier published value.
[b] Corrected (from 340.45±0.04) as explained in the text.

beam energy resolution used in this experiment ($R\approx$ 0.05%) was not particularly high by present-day standards. At high resolutions ($R\approx$0.02%), a $(\text{yield})^{\frac{2}{3}}$ plot is distinctly more linear than a $(\text{yield})^1$ plot.

Browne *et al.* (Br 60, Br 64) have made an extensive series of measurements to compare the $Li^7(p, n)Be^7$ threshold energy with the energy of Po^{210} α particles. Their latest results (Br 64) are expressed as follows: assuming a threshold energy of 1880.7 keV, the energy of Po^{210} α particles is 5304.2±2.0 keV. The best value for the Po^{210} α-particle energy is now 5304.51±0.47 keV (Wa 64), so that the threshold energy becomes 1880.8±0.7 keV. In obtaining this energy ratio result, Browne *et al.* used both H^+ and H_2^+ beams. Because it has been recognized (Da 60, Wa 62, Bo 63a) that resonance and threshold shapes measured with H_2^+ ions can be quite different from those obtained with protons (H^+), it was necessary to fit the H_2^+ neutron yield curve with a theoretical formula in order to obtain the proper intercept. In spite of this difference in procedure, it still seems reasonable to include Browne's value along with the other results using $(\text{yield})^{\frac{2}{3}}$ extrapolations.

Four pre-1958 measurements have been excluded from the threshold energy list. The electrostatic measurement of Herb *et al.* (He 49) which gave 1882.2±1.9 keV and the velocity measurement of Shoupp *et al.* (Sh 49) which gave 1881.2±1.9 keV suffer from inadequate beam energy resolution and probably also from target contamination problems. Sturm and Johnson (St 51) compared the threshold energy with the energy of α particles from RaC′. The sources used had not been freshly prepared and it is now known that fresh sources are a necessity for precise experiments. Jones *et al.* (Jo 54), using inelastic scattering techniques, compared the threshold energy with the energy of the first excited state of Mg^{24}. It is possible to obtain a corrected threshold energy by combining the energy ratio with the recent precision measurement of the energy of Mg^{24*} made by Murray *et al.* (Mu 65); the result is 1879.6±1.0 keV. Apart from the fact that this experiment falls into the "old" group, the exclusion of this result from the weighted mean can also be made on the following grounds: (a) The intercalibration of the two electrostatic analyzers used in the experiment was made with H_2^+ beams but no analysis of the type now known to be necessary (Da 60, Wa 62, Bo 63a, Br 64) was made. (b) Linear extrapolation of the yield was made. (c) The results also depend on a line-shape analysis since the inelastic scattering was performed on a narrow resonance. All of these factors contribute sufficient uncertainty in the reliability of the result to warrant its exclusion.

It must be emphasized that although the threshold energy 1880.60±0.07 keV is recommended for calibration purposes [i.e., the intercept of a $(\text{yield})^{\frac{2}{3}}$ extrapolation], this value is not appropriate for a Q-value calculation; the *true* threshold probably is about 150 eV higher.

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

The results for the $F^{19}(p, \alpha\gamma)O^{16}$ resonances at 340.46 and 872.11 keV are shown in Tables III and IV. These resonances tend to be less suitable for calibration purposes because of their appreciable widths. It is unfortunate that more measurements of the widths are not available; a few additional measurements would increase the usefulness of these resonances considerably.

The weighted mean of the 340-keV resonance is completely dominated by the result of Seagrave *et al.* (Se 64) which has an assigned uncertainty that is an order of magnitude smaller than the other errors. The instrument with which this experiment was performed is certainly capable of a precision of 0.01%, as was demonstrated by other measurements with the same apparatus (Ro 66). However, it appears overly optimistic to expect that the position of a resonance peak can be identified with an uncertainty of only 40 eV when the width of the resonance is 2.4 keV. This seems especially true in view of the fact that no uncertainty is quoted for the width measurement. Therefore, even though E_R= 340.46 keV is retained as the recom-

Table IV. $F^{19}(p, \alpha\gamma)O^{16}$ resonance energies.

E_R(keV)	Γ(keV)	Method	Reference
872.4 ±0.4	4.5±0.3	Absolute electrostatic	Bo 59
872.33±0.27[a]		Absolute magnetic	Be 61
871.80±0.25[b]	4.8±0.2	Absolute magnetic	Ry 62

Weighted mean: E_R=872.11 keV

e_{int}=0.17 keV

e_{ext}=0.20 keV

Recommended: E_R=872.11±0.20 keV; Γ=4.7±0.2 keV

[a] Corrected (from 872.3±0.5) as explained in the text.
[b] Supercedes an earlier published value.

mended energy, the standard deviation, ±0.04 keV, is artificially small.

D. $C^{13}+p$

The $C^{13}(p, \gamma)N^{14}$ resonance at 1747.6 keV and the $C^{13}(p, n)N^{13}$ threshold at 3235.7 keV have received too little attention in view of their importance as energy standards. A single absolute measurement of the resonance energy is available and only two laboratories have produced absolute values for the threshold energy. These results are shown in Table V. It is to be hoped that additional measurements will be made in the near future.

The data of Bondelid and Kennedy (Bo 59) for the $C^{13}(p, \gamma)N^{14}$ resonance gave a midpoint energy of 1747.6±0.9 keV. The same data were later re-analyzed (Bo 63) by taking into account the discrete energy loss effect and a *true* resonance energy of 1747.06±0.53 keV was obtained. In Table V, the midpoint value is listed as the one appropriate for calibrations in accordance with the discussion in Sec. V. Similarly, the $(\text{yield})^{\frac{2}{3}}$ extrapolated value of 3236.9±1.6 keV is given for the threshold energy (Bo 64); the same data gave 3237.2±1.6 keV when linearly extrapolated (Bo 59) and 3237.1±1.6 keV when analyzed with the discrete energy loss theory (Bo 64). Bondelid and Whiting (Bo 64) point out that the $(\text{yield})^{\frac{2}{3}}$ extrapolated value is correct for their beam energy resolution (0.03%) and will be slightly different for other conditions. The Rice measurements (Be 61, Bo 66) were made with similar resolutions, so the three results can properly be averaged.

Table V. $C^{13}+p$ calibration energies.

$C^{13}(p, \gamma)N^{14}$			
E_R(keV)	Γ(keV)	Method	Reference
	0.077±0.012	Resonance absorption	Ha 59
1747.6±0.9	0.075±0.050	Absolute electrostatic	Bo 59

$C^{13}(p, n)N^{13}$		
E_{th}(keV)	Method	Reference
3235.41±1.1[b]	Absolute magnetic	Be 61
3236.9 ±1.6[a]	Absolute electrostatic	Bo 64
3235.51±1.1[c]	Absolute magnetic	Bo 66

Weighted mean: $E_{th}=3235.7$ keV
$e_{int}=0.7$ keV
$e_{ext}=0.4$ keV
Recommended: $E_{th}=3235.7\pm0.7$ keV

[a] Supercedes an earlier published value.
[b] Corrected (from 3235.3±1.5) as explained in the text.
[c] Corrected (from 3235.4±2.4) as explained in the text.

VII. CALIBRATION POINTS FOR HIGHER ENERGY PROTONS

Table VI lists the results of all the absolute measurements of (p, n) thresholds for bombarding energies between 4.2 and 9.5 MeV. These values are from three sources—the absolute magnetic measurements made at Rice (Be 61, Bo 66) and at Zürich (Ry 61) and the comparison of threshold energies with α-particle energies made at Harwell (Fr 65). The agreement among the results is satisfactory although it is not as good as at lower energies.

At these high bombarding energies, the normal neutron background tends to be large and to obscure the relatively weak neutron yield at threshold. Therefore, extraordinary precautions must usually be taken, such as using thin targets and stopping the proton beam only after it is some distance away from the detector area (Ph 64); alternatively, the beam can be chopped and the target radioactivity (annihilation radiation from β^+ decay) can be detected (Fr 65).

Recently, several narrow levels have been discovered at high excitation energies in light nuclei. The small widths of these levels result from the fact that they are forbidden (at least in first order) by isobaric spin conservation to decay by particle emission. One such level that is of interest from the calibration standpoint is the first $T=\frac{3}{2}$ level of N^{13}. This state has been observed in the $B^{11}(He^3, n)N^{13}$ reaction (which is not isobaric-spin forbidden) by Adelberger and Barnes (Ad 65) who determined that the excitation energy is 15.068±0.008 MeV and that the width is less than 20 keV. This level has also been observed (Br 66) in the scattering of protons by C^{12} (an isobaric-spin forbidden reaction which proceeds only by virtue of a small $T=\frac{1}{2}$ impurity in the state); the width was found to be less than 1 keV. Since the scattering anomaly is quite pronounced (Br 66), this resonance provides a convenient calibration point at a proton bombarding energy of 14.233±0.008 MeV (see Table VII).

Other narrow, T-forbidden resonances should also be suitable for calibration purposes. Two candidates are to be found, for example, in the scattering (and, presumably, also in the capture) of protons by O^{16}. Narrow levels (Γ<5 keV) have been found at bombarding energies of 12.671 and 13.215 MeV (Ha 63). These states appear to be the analogs of N^{17} excited states. The analogue of the ground state was not observed; it may be sufficiently narrow to have escaped detection. Recent measurements (Wi 66) have shown that the previous results for the lower $O^{16}+p$ resonance are somewhat inaccurate. The resonance energy is 12.728±0.010 MeV and the width is Γ<2 keV (Wi 66). The scattering anomaly is well defined so that this resonance energy should be a most useful high-energy

TABLE VI. Higher energy (p, n) threshold energies.

Reaction	E_{th}(keV)	Method	Reference	Recommended value
$F^{19}(p, n)Ne^{19}$	4233.34±1.5[a]	Absolute magnetic	Be 61	4234.3±0.8 keV
	4234.7 ±1.0	Absolute magnetic	Ry 61	
$Al^{27}(p, n)Si^{27}$	5794.5 ±2.4[b]	Absolute magnetic	Bo 66	
	5802.9 ±3.8	ThC α (6089.7 keV)	Fr 65	5796.9±3.8 keV
$S^{34}(p, n)Cl^{34}$	6451.1 ±4.5	ThC α (6089.7 keV)	Fr 65	
$Ni^{60}(p, n)Cu^{60}$	7023.84±3.9[c]	Absolute magnetic	Bo 66	
$Fe^{54}(p, n)Co^{54}$	9202.7 ±4.8	ThC′ α (8786.4 keV)	Fr 65	
$Ni^{58}(p, n)Cu^{58}$	9516.32±3.5[d]	Absolute magnetic	Bo 66	
	9512.9 ±5.0	ThC′ α (8786.4 keV)	Fr 65	9515.2±2.9 keV

[a] Corrected (from 4233.2±2.0) as explained in the text.
[b] Corrected (from 5794.3±4.7) as explained in the text.
[c] Corrected (from 7023.6±7.1) as explained in the text.
[d] Corrected (from 9516.0±7.8) as explained in the text.

calibration point. An improvement in the precision of the above result should be forthcoming (Wi 66).

Another calibration point that is available in the $C^{12}+p$ system is the as yet unobserved (p, n) threshold. The Q value for the $C^{12}(p, n)N^{12}$ reaction can be obtained from the 1964 least-squares adjustment of atomic masses (Ma 65) and the threshold is readily calculated to be 19.684±0.008 MeV (see Table VII). Although detection of the threshold neutrons at such a high bombarding energy will be difficult, the short half-life of N^{12} means that the detection of the induced radioactivity should be relatively easy.

VIII. $O^{16}+d$ THRESHOLD ENERGIES

The threshold energy for the $O^{16}(d, n)F^{17}$ reaction has been measured by Bondelid *et al.* (Bo 60) who found $E_{th}=1829.2\pm0.6$ keV. For the purposes of calibrating high-energy electrostatic accelerators, this reaction may be used by reversing the roles of the target and projectile so that the reaction becomes $H^2(O^{16}, n)F^{17}$ (Go 58). By accelerating oxygen ions in various charge states and determining the threshold positions, a magnetic beam analyzer can be calibrated at equivalent proton energies of 6.45, 9.29, 14.52, and 25.63 MeV with considerable precision (see Table VIII).

IX. HELIUM ION ENERGIES

Only three absolute measurements have been made of helium-ion-induced neutron thresholds. These are listed in Table IX—two for the $C^{12}(He^3, n)O^{14}$ reaction and one for the $Li^6(He^3, n)B^8$ reaction. The threshold energies for several other reactions can be calculated from the atomic masses given by Mattauch *et al.* (Ma 65); these are also shown in Table IX. By using singly and doubly charged helium ions, these thresholds will provide calibration points for magnetic analyzers up to an equivalent proton energy of 60.4 MeV. Although none of the higher energy (α, n) thresholds have been observed, these reactions are probably the best prospects for precision calibrations of magnets at high field strengths.

Some (α,γ) resonances are also useful as calibration points. Of particular interest in the resonance at $E_a=$

TABLE VII. $C^{12}+p$ calibration energies.

Resonance excitation of first $T=\frac{3}{2}$ state of N^{13}				
Reaction	E_x(MeV)	E_R(MeV)	Γ(keV)	Reference
$C^{12}(p, p)C^{12}$	15.068±0.008	14.233±0.008	<20	Ad 65[a]
			<1	Br 66
Neutron threshold (calculated from 1964 masses)				
Reaction	Q(MeV)	E_{th}(MeV)		Reference
$C^{12}(p,n)N^{12}$	−18.14645±0.007	19.684±0.008		Ma 65

[a] Used the $B^{11}(He^3, n)N^{13}$ reaction.

TABLE VIII. $O^{16}+d$ threshold energies.

$O^{16}(d,n)F^{17}$		
E_{th}(keV)	Method	Reference
1829.2±0.6	Absolute electrostatic	Bo 60
$H^2(O^{16}, n)F^{17}$		
Charge state	O^{16} energy (MeV±keV)	Equivalent proton energy[a] (MeV±keV)
+3	14.5255±5	25.627±9
+4	14.5250±5	14.519±5
+5	14.5245±5	9.292±3
+6	14.5240±5	6.452±2

[a] Proton energy in the same magnetic field as required for the oxygen ion at threshold.

TABLE IX. Helium ion threshold energies.

Experimentally determined values			
Reaction	E_{th} (keV)	Method	Reference
$C^{12}(He^3, n)O^{14}$	1436.2±0.9	Absolute electrostatic	Bu 61
	1436.9±0.6	Absolute velocity	Ro 66
Weighted mean: $E_{th}=1436.7\pm0.5$ keV			
$Li^6(He^3, n)$	2966.1±1.7	Absolute electrostatic	Du 58

Calculated from 1964 masses (Ma 65)

Reaction	E_{th} (MeV±keV)	Equivalent proton energy[a] (MeV±keV) For He⁺	Equivalent proton energy[a] (MeV±keV) For He⁺⁺
$Li^6(He^3, n)B^8$	2.9650±1.5	8.8826±4.5	2.2198±1.1
$Li^6(\alpha, n)B^9$	6.6239±2.6	26.345 ±11	6.5844±2.6
$Li^7(\alpha, n)B^{10}$	4.3843±1.9	17.4321±7.4	4.3568±1.9
$C^{12}(He^3, n)O^{14}$	1.4366±0.5	4.3026±1.5	1.0753±0.4
$C^{12}(\alpha, n)O^{15}$	11.3463±1.7	45.1553±6.8	11.2857±1.7
$N^{14}(\alpha, n)F^{17}$	6.0888±0.8	24.2148±3.1	6.0520±0.8
$N^{15}(\alpha, n)F^{18}$	8.1324±1.5	32.3509±6.1	8.0855±1.5
$O^{16}(He^3, n)Ne^{18}$	3.7987±5.7	11.382 ±17	2.8444±3.6
$O^{16}(\alpha, n)Ne^{19}$	15.1761±2.0	60.4279±8.0	15.1028±2.0

[a] Proton energy in the same magnetic field as required for the helium ion at threshold.

3199.8±1.0 keV in the $Mg^{24}(\alpha,\gamma)Si^{28}$ reaction (Ry63). The width of this resonance is 1.8±0.3 keV and the increase of yield from a semi-thick target is quite pronounced, thereby rendering the resonance suitable for calibration purposes.

TABLE X. Summary of proton calibration energies.

Reaction	E_R or E_{th} (keV)	Γ (keV)
$F^{19}(p, \alpha\gamma)O^{16}$	340.46±0.04	2.4 ±0.2
$F^{19}(p, \alpha\gamma)O^{16}$	872.11±0.02	4.7 ±0.2
$Al^{27}(p, \gamma)Si^{28}$	991.90±0.04	0.10 ±0.02
$C^{13}(p, \gamma)N^{14}$	1747.6 ±0.9	0.077±0.012
$Li^7(p, n)Be^7$	1880.60±0.07	
$C^{13}(p, n)N^{13}$	3235.7 ±0.7	
$F^{19}(p, n)Ne^{19}$	4234.3 ±0.8	
$Al^{27}(p, n)Si^{27}$	5796.9 ±3.8	
$S^{34}(p, n)Cl^{34}$	6451.1 ±4.5	
$Ni^{60}(p, n)Cu^{60}$	7023.6 ±3.9	
$Fe^{54}(p, n)Co^{54}$	9202.7 ±4.8	
$Ni^{58}(p, n)Cu^{58}$	9515.2 ±2.9	
$O^{16}(p, p)O^{16}$	12 728 ±10	<2
$C^{12}(p, p)C^{12}$	14 233 ±8	<1
$C^{12}(p, n)N^{12}$	19 684 ±8	

X. SUMMARY

The precision of absolute energy measurements is now sufficiently high that there seems to be little likelihood that the recommended values for the primary, low-energy calibration points will change by significant amounts due to subsequent experiments. Unless future absolute measurements are analyzed by taking into account the known effects of surface contaminants and the discrete energy loss of the incident particles, there also seems to be little prospect that the precision can be improved. All users who would take advantage of the increased precision also would be forced to make detailed analyses of the yield curves rather than merely take the midpoint of thick-target resonance curves or the intercept of a $(\text{yield})^{\frac{2}{3}}$ extrapolation. We have essentially reached the limit of these quick but crude methods and the next advance in precision will require much more sophisticated data analysis techniques.

At the higher energies ($E_p \gtrsim 3$ MeV), there is still considerable room for improvement. Instruments in use at the present time can be used to provide a greater amount of data for neutron thresholds and isobaric-spin forbidden resonances up to proton bombarding energies of 10 or 15 MeV, but until some significant improvements are made, direct absolute measurements at higher energies will probably not be possible. The use of inverse reactions and calculated threshold energies must serve until these improvements are made.

Table X summarizes the proton calibration points;

Tables VIII and IX contain the deuteron and helium ion data, respectively.

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