has a standard error within five percent but refers to an effective energy of about 14.6 Mev since a thick target was used. The solution used was chemically analyzed to determine the copper concentration. Based on weights of the ingredients, the copper concentration was 4.1% lower. Because of the observed tendency of the copper salt to lose weight upon weighing, the concentration from the chemical analysis was used. Other measured values of the cross section are 510 mb (±7%) by Forbes at 14.1 Mev,[11] 482 mb (±15%) by Paul and Clarke at 14.5 Mev,[3] and 556 mb (±5%) by Yasumi at 14.1 Mev.[10] Only the latter value includes the $K$-capture correction factor of 1.043.

With a steady 14-Mev source and grounded target, the neutron flux can be easily measured to a 2% if both a recoil proton telescope and associated particle counter are employed. The remaining errors are small and can be reduced to less than 1.0% (total) with a sufficiently strong source. As a result, activation cross sections accurate to 2–3% can be attained with the present technique.

*Note added in proof.* J. M. Ferguson and W. E. Thompson, Phys. Rev. **118**, 228 (1960), have obtained a value of 507±45 mb for the $Cu(n,2n)$ cross section at 14.74 Mev. A 2.0% correction was made for $K$ capture.

[11] S. G. Forbes, Phys. Rev. **88**, 1309 (1952).


### ACKNOWLEDGMENTS

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# Comparison of $Po^{210}$ Alpha-Particle Energy with the $Li^7(p,n)Be^7$ Reaction Threshold Energy*

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Recent absolute measurements of the $Po^{210}$ alpha-particle energy disagree with the older value used as the standard for many nuclear reaction energy measurements. A new comparison with the $Li^7(p,n)Be^7$ reaction threshold energy was made using the Notre Dame electrostatic accelerator and broad-range spectrograph. Four separate methods of comparison were used. In the first three the threshold was run and then protons or deuterons were scattered from appropriate targets so that the scattered group was recorded on the spectrograph plate near the alpha group from a source placed at the target position. First, the spectrograph and, second, the beam analyzer were used to compare particle momenta. Third, with both fields held constant after the threshold was run with the molecular beam, deuterons were scattered, giving particles of the same $B\rho$ as the alphas. In the fourth method several reaction energies that are precisely known in terms of the $Li^7(p,n)Be^7$ reaction threshold energy were measured in terms of the $Po^{210}$ alpha-particle energy. These were the $Mg^{24}(d,d')Mg^{24*}$ reaction to the first excited state of $Mg^{24}$ and the $N^{14}(d,p)N^{15}$ reaction leading to three excited states of $N^{15}$. The four measurements agree and give 5.3086±0.003 Mev for $Po^{210}$ alpha-particle energy based on 1.8811 Mev for the $Li^7(p,n)Be^7$ reaction threshold energy.

## I. INTRODUCTION

THE discrepancies between nuclear mass values obtained by mass spectroscopy and those derived from nuclear reaction energies are usually discussed in terms of a single energy standard for nuclear reaction energies. There are, however, two widely used standards: the $Li^7(p,n)Be^7$ reaction threshold energy and the energy of alpha particles emitted by $Po^{210}$. As will be discussed below, an earlier comparison of these two energies[1] was consistent with the early absolute determination of each. Recent absolute determinations of the $Po^{210}$ alpha-particle energy,[2,3] however, indicate that the previously accepted value of this energy,[4] 5.2988 Mev, is low. Because of the importance of the $Po^{210}$ alpha-particle energy to much of the pre-

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] W. J. Sturm and V. Johnson, Phys. Rev. **83**, 542 (1951).

[2] E. R. Collins, C. D. McKenzie, and C. A. Ramm, Proc. Roy. Soc. (London) **A216**, 216 (1953).

[3] F. A. White, F. M. Rourke, J. C. Sheffield, R. P. Schuman, J. R. Huizenga, Phys. Rev. **109**, 437 (1958).

[4] See for example E. N. Strait, D. M. Van Patter, W. W. Buechner, and A. Sperduto, Phys. Rev. **81**, 747 (1951); S. F. Zimmerman, thesis, Massachusetts Institute of Technology, 1955 (unpublished); S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **74**, 196 (1959).

TABLE I. $Li^7(p,n)Be^7$ reaction threshold energy.

| Method of measurement | Energy standard | Value (Mev) | Uncertainty (kev) |
|---|---|---|---|
| Electrostatic analyzer[a] | Absolute | 1.8822 | 1.9 |
| Rf velocity determination[b] | Absolute | 1.8812 | 1.9 |
| Electrostatic analyzer[c] | $Po^{214}$ alpha-particle energy 7.6804 Mev[d] | 1.8813 | 0.7 |
| Electrostatic analyzers[e] | $Au^{198}$ gamma-ray energy 411.770±0.036 kev[f] | 1.8814 | 1.1 |
| Electrostatic analyzers[e] | $Co^{60}$ gamma-ray energy 1332.5±0.3 kev[g] | 1.8797 | 1.1 |
| Electrostatic analyzer[h] | Absolute | 1.8812 | 0.9 |
| | Average value used in this work | 1.8811 | |

[a] See reference 6.
[b] See reference 8.
[c] See reference 1.
[d] See reference 12.
[e] The excitation energy of the first state in $Mg^{24}$ was measured using the $Mg^{24}(p,p')Mg^{24*}$ reaction and compared with the energy of the de-excitation gamma ray from this state. See reference 9.
[f] See reference 10.
[g] See reference 11.
[h] See reference 7.

cision work done in low-energy nuclear physics and in particular because of its use in the calibration of the now widely used broad-range spectrograph,[5] it is important to recompare the $Po^{210}$ alpha-particle energy with the $Li^7(p,n)Be^7$ reaction threshold energy.

The $Li^7(p,n)Be^7$ reaction threshold energy has been measured with considerable precision in several laboratories using various methods.[1,6–9] Some of these are absolute and some are based on other absolute energy measurements.[10–12] Table I summarizes these results. The value 1.8811±0.0005 Mev is adopted for this energy.

The various previous determinations of the $Po^{210}$ alpha-particle energy are listed in Table II. In compiling this table, where a measurement gave the magnetic rigidity ($B\rho$), the kinetic energy corresponding to this value of $B\rho$ has been taken from the tables of Enge.[13] It should be noted that the higher value of 1.8822 Mev used by Sturm and Johnson[1] for the threshold energy led to 5.298±0.005 Mev for the energy of $Po^{210}$ alpha particles, thus appearing to confirm the results of the early absolute measurements[14,15] and supporting the value previously used for nuclear-reaction-energy measurements.[4] If the presently adopted value for the threshold energy is used, the Sturm and Johnson measurement yields 5.295 Mev as shown in Table II. As late as 1954 the value suggested by Briggs in a review article[12] was 5.3006±0.0026 Mev. The absolute measurement of magnetic rigidity by Collins, McKenzie, and Ramm[2] and the absolute voltage determination of White *et al.*[3] give values for the $Po^{210}$ alpha-particle energy as much as 0.18% above the older values and outside the stated errors.

In the present work, the use of a broad-range spectrograph in conjunction with an electrostatic accelerator allowed not only a direct comparison of the $Po^{210}$ alpha-particle energy with the $Li^7(p,n)Be^7$ reaction threshold energy but also an indirect comparison through a few well-determined $Q$ values. These are listed in Table III. The value for the $Mg^{24}$ excitation energy used here is 1.3700±0.0005 Mev which is the average of the two direct measurements[9,16] of the $Mg^{24}(p,p')Mg^{24*}$ reaction energy based on the $Li^7(p,n)Be^7$ reaction threshold energy. The three $Q$ values listed for the $N^{14}(d,p)N^{15*}$ reaction[17] are some of the very few that have been measured against the lithium threshold with sufficient accuracy to be useful for a comparison of energy standards.

It should be noted that the excitation energy of the first state of $Mg^{24}$ is one of a chain of energies used in obtaining the two values, listed in Table I, for the lithium threshold based on absolute gamma-ray energy

TABLE II. $Po^{210}$ alpha-particle energy.

| Method of measurement | Reference energy[a] | Energy value (Mev) | Uncertainty (kev) |
|---|---|---|---|
| Magnetic deflection[b] | Absolute | 5.2985 | 6.4 |
| Magnetic deflection[c] | $Po^{214}$ alpha-particle energy 7.6804 Mev[d] | 5.3011 | 2.0 |
| Magnetic deflection[e] | $Po^{214}$ alpha-particle energy 7.6804 Mev[d] | 5.2988 | 2.1 |
| Electrostatic deflection[f] | $Li^7(p,n)Be^7$ reaction threshold energy 1.8811 Mev[g] | 5.2954 | 5.0 |
| Magnetic deflection[h] | Absolute | 5.3043 | 2.9 |
| Magnetic deflection and electrostatic acceleration[i] | Absolute | 5.3054 | 1.0 |

[a] In cases of relative measurements the value quoted is obtained from the measured energy ratio and listed reference energy.
[b] See reference 14.
[c] E. Rutherford, C. E. Wynn-Williams, W. B. Lewis, and B. V. Bowden, Proc. Roy. Soc. (London) **A139**, 617 (1933).
[d] See reference 12.
[e] See reference 15.
[f] See reference 1.
[g] Value adopted for this work.
[h] See reference 2.
[i] See reference 3.

[5] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).
[6] R. G. Herb, S. C. Snowdon, and O. Sala, Phys. Rev. **75**, 246 (1949).
[7] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1601 (1959).
[8] W. E. Schoupp, B. Jennings, and W. Jones, Phys. Rev. **76**, 502 (1949).
[9] K. W. Jones, R. A. Douglass, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **94**, 947 (1954).
[10] D. E. Muller, H. C. Hoyt, D. J. Klein, and J. W. M. DuMond, Phys. Rev. **88**, 775 (1952).
[11] G. Lindstrom, A. Hedgram, and D. E. Alburger, Phys. Rev. **89**, 1303 (1953).
[12] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).
[13] H. A. Enge, "Table of Charged Particle Energies versus Magnetic Field Strengths times Orbit Radius," printed in Norway. The constants used are those given in J. W. M. DuMond and E. R. Cohen, Revs. Modern Phys. **25**, 706 (1953).
[14] S. Rosenblum and G. DuPouy, Compt. rend. **194**, 1919 (1932); S. Rosenblum and G. DuPouy, J. Phys. radium **4**, 262 (1933).
[15] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 235 (1934).
[16] D. J. Donoghue, K. W. Jones, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **89**, 824 (1953).
[17] R. A. Douglas, J. W. Broer, R. Chiba, D. F. Herring, and E. A. Silverstein, Phys. Rev. **104**, 1059 (1956).

measurements. As the intent of the present experiments is to provide a consistent nuclear energy scale, whether based on the $Li^7(p,n)Be^7$ threshold or on the $Po^{210}$ alpha energy, the direct comparison of the alpha-particle energy alone with the gamma-ray energy scale will not be made.

## II. APPARATUS

Because the beam analyzer and spectrograph used in these measurements are new and have not been described before, a brief discussion of the important features is given here. A schematic drawing of the equipment is shown in Fig. 1. The positive ion beam from the electrostatic accelerator passes through a beam analyzer, then through an electrostatic quadrupole lens (not used in this experiment) and finally into the target chamber of a broad-range spectrograph.

The beam analyzer has a uniform magnetic field through a gap of $\frac{1}{2}$ inch. The pole pieces are shaped so that the beam on entering and leaving is perpendicular to the field boundary when deflected through angles of 30, 45, 60, 90, or $-30$ degrees. This gives focusing in the plane of the gap only, which is desirable where the beam to be used at a considerable distance from the image point. The shape of the target room required that the spectrograph target chamber be mounted such that the 30-degree deflection is used. To obtain the desired resolution with a practical object slit width, a trajectory radius of 61.5 cm is used. For 30-degree deflection an object and image distance of 224 cm is required. A field of 10 500 gauss then permits deflection of 5-Mev $He^{4+}$ ions.

All iron is Armco magnetic iron, twice annealed and carefully machined. Current for the magnet is provided by a well-regulated supply. The error signal for the regulator is obtained by comparing the voltage across a standard resistor carrying the magnet current with the voltage across a helipot connected to a reference battery. A proton resonance fluxmeter measures the magnetic field.

Entrance and exit slits with micrometer adjustments

TABLE III. $Q$ values used for energy reference.

| Tabulated energy | Value[a] (Mev) | Uncertainty (kev) |
|---|---|---|
| Excitation of 1.37-Mev level in $Mg^{24}$ | 1.3697[b] | 0.7 |
| Excitation of 1.37-Mev level in $Mg^{24}$ | 1.3703[c] | 2 |
| $Q$ of $N^{14}(d,p)N^{15}$ to 7.31-Mev Level of $N^{15}$ | 1.308[d] | 1.5 |
| $Q$ of $N^{14}(d,p)N^{15}$ to 7.58-Mev level of $N^{15}$ | 1.045[d] | 1.5 |
| $Q$ of $N^{14}(d,p)N^{15}$ to 8.32-Mev level of $N^{15}$ | 0.296[d] | 1 |

[a] All listed $Q$ values are based on 1.8811 Mev for the $Li^7(p,n)Be^7$ reaction threshold energy.
[b] See reference 9.
[c] See reference 16.
[d] See reference 17.

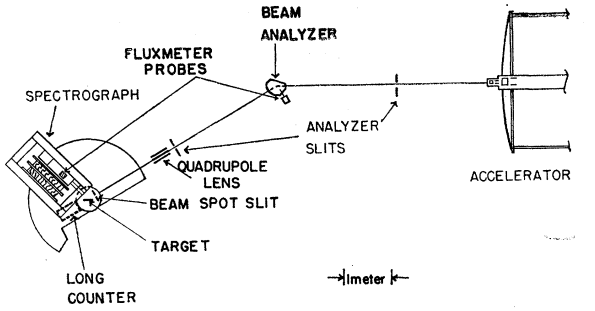


FIG. 1. Schematic diagram of apparatus. The path of the beam from accelerator to target is shown. An outline of the pole piece, only, of the analyzer magnet is shown.

are placed at the foci of the analyzer. Most work is done with $\frac{1}{2}$-mm slits which give an energy resolution of 0.08%. The difference in beam current onto the two exit slits provides a signal for stabilizing the accelerator voltage.

Upon entering the target chamber the beam passes through a $\frac{1}{2}\times 3$-mm slit placed 4 cm in front of the target. The beam spot on the target outlined by this slit forms the object for the spectrograph. The jaws of this slit are insulated and metered to allow centering of the beam on the opening, using the electrostatic deflection between the accelerator and beam analyzer. A second slit, slightly larger than this "object" slit, so that it "scrapes" the beam, reduces the number of particles reaching the target after scattering from the edges of the object slit.

The broad-range magnetic spectrograph is very similar to the one previously described,[5] the principle differences being (1) an improved target chamber that allows rotation under vacuum, (2) placing of the magnet coils on only one side of the gap which allows rotation of the spectrograph back to 142 degrees and (3) a double-width camera box and plate holder with two sets of nuclear track plates side by side so that eight exposures may be made with one loading of plates. A calibration curve relating plate position to trajectory radius was obtained by placing the alpha-particle group from $Po^{210}$ at various points along the plate using a series of magnetic fields. The shape of this calibration curve obtained with various fields was checked at constant field by scattering a beam of fixed energy from targets of different masses, thus putting a series of groups of known energy ratios along the plate. The shape of the curve was found to be constant, within the accuracy of the measurements, over the range of fields used, provided the field was brought up from zero each time. Differential hysteresis effects were, however, observed and are discussed below.

To give the scattering angle, a scale was laid out along the perimeter of the base on which the spectrograph rotates. This was done by mounting a transit on the spectrograph with the axes of transit and spectrograph coincident, sighting the transit at a mark about

30 ft away, and reading its angle scale as the spectrograph was rotated. The zero of the angle scale was found by allowing the beam to come through the spectrograph gap with field off. A needle was placed at the center of the target chamber (on the axis of rotation) and the spectrograph moved until the shadow of this needle cast by the beam coincided with the shadow of a second needle placed in the middle of the gap. Scattering angles were checked by observing the ratio of the energies of deutrons scattered from gold and from lithium. Angles are known to within $\pm 0.03$ degree.

### III. GENERAL METHODS

This section contains methods applying to all of the measurements. Specific methods for each measurement are given in the next section. For threshold determinations lithium targets, prepared by evaporating natural lithium metal onto thin Formvar or thick tantalum backings, were placed in the target chamber of the broad-range spectrograph. For most runs the targets on the thin backings were mounted on the regular target holder in the middle of the chamber. In all cases the target chamber wall between target and detector was a 0.010-inch thick steel strip. To check any effect of scattering from the thicker aluminum portions of the target chamber a run was made with a 1-inch thick aluminum slab interposed between target and detector.

There are several variables present in a $Li^7(p,n)Be^7$ threshold energy determination which may affect the shape of the yield curve and hence the threshold energy: (1) the solid angle subtended by the neutron detector, (2) the $Li^7$ target thickness, and (3) input proton beam energy spread. The input beam energy spread is due to finite slit widths in the energy defining analyzer, Doppler shift due to thermal motion of the target atoms, and, in the case of thresholds taken with a $H_2^+$ beam, motion of the protons in the $H_2^+$ molecule about the molecular center of mass. From threshold to a few kev above threshold the total cross section, to a good approximation, varies as the square root of the energy above the threshold.[18] For a thick target, with $4\pi$ detector geometry, up to the input energy where protons traversing the entire target are just reduced in energy to the threshold energy, the $\frac{1}{2}$ power dependence of thin-target yield on proton energy above threshold becomes approximately a $\frac{3}{2}$ power dependence. A symmetrical input beam spread will affect the shape of this yield curve only where a plot of yield versus proton energy has a large second derivative. This is the case only at threshold so that once the input proton energy is above threshold by the half-width of the energy spread, the effect of input beam energy spread on the yield curve is negligible.

It follows then that a yield curve which may be extrapolated to zero yield to obtain a threshold energy with minimum ambiguity may be taken with (1) a detector that will accept the entire neutron cone up to incident proton energies which are above threshold by more than the target thickness and (2) a target whose thickness is several times greater than the energy spread in the incident proton beam. Under these conditions the yield curve has essentially a linear dependence on proton energy above the cusp caused by proton energy spread and below the point of inflection which occurs at the energy where protons traversing the entire target are just reduced in energy to threshold energy. In the present experiment a check on the effect of the solid angle subtended by the detector was made in a series of runs in which the target was at various distances from the shielded long counter used as a detector. In one run the target was in immediate proximity to the counter. The yield curves did not differ from the majority of yield curves obtained with the geometry shown in Fig. 1. The minimum target thickness used gave about 8-kev energy loss for protons of threshold energy which is at least four times the incident energy spread.

The practice in running thresholds with the atomic beam was to change the beam analyzer proton resonance fluxmeter frequency in steps of 1 kilocycle (0.27 kev) and then to bring the field to the resonance value. A yield curve then consisted of a plot of scaler counts per unit integral of beam intensity versus frequency. This frequency is proportional to momentum, but over the small ranges involved it varies linearly with energy. After correcting the yield curve for background, a linear extrapolation of the region between the cusp and the point of inflection corresponding to target thickness was taken to be the threshold frequency. This frequency then corresponded to a beam energy distribution centered at the threshold energy.

After the threshold had been found, other targets were substituted for the lithium one and particles scattered from them allowed to enter the spectrograph. Bombardment was continued for a sufficient time to give enough particles in the group on the spectrograph plate to be easily counted and yet give good statistical accuracy.

The target holder was now removed and a $\frac{1}{2}$-mm diameter silver wire on which polonium had been deposited was clamped to the holder so as to be at the exact position of the beam spot on a target. An exposure was then made to record the alpha particles. The positions of the beam spot and the polonium source wire were measured with a travelling microscope relative to a fiducial mark on the target holder. A stop in the target chamber allowed the target holder to be placed in the same position each time. The beam spot position was checked several times both by observing the darkened area on targets and by clamping a bit of nuclear track plate to the target holder, irradiating with the beam, developing and observing. A third check was made by taking one run in which the beam was scattered from the silver of the source wire itself.

[18] H. W. Newson, R. M. Williamson, K. W. Jones, J. H. Gibbons, and H. Marshak, Phys. Rev. **108**, 1294 (1957).

Freshly made polonium sources were always used because it is observed that the polonium slowly diffuses into the silver so that after a few days the alpha particles have an increased spread in energy and the group on the nuclear track plate no longer has a sharp, well-defined high-energy edge. To prepare a source, a length of pure silver wire is cleaned with alcohol or acetone, then with hydrochloric acid, and then with distilled water, and placed in a solution of polonium chloride plus hydrochloric acid for a period of three to thirty minutes, depending on the activity of polonium solution and the source strength desired. The wire is removed from the solution, being careful that no droplets remain on it, air dried and clamped on the target holder.

The combination of bombarding energy, target, angle of observation, and spectrograph field was chosen so that the group of alpha particles from the polonium lay near the group of elastically scattered particles on the spectrograph plate. In some cases the groups actually overlapped. This caused no difficulty in counting because track lengths of the two types of particle are quite different. Knowledge of the spectrograph calibration (trajectory radius vs position on plate) was needed only to find the small relative *difference* in trajectory radius between the two particle groups. This entails knowing only the *shape* of the calibration curve over small distances, not the absolute calibration.

In most cases groups from more than one target element appeared on the plate for each exposure. By using the spectrograph calibration curve as many determinations as target elements could be made of the bombarding energy. In all cases one of the elements was carbon. This provided a check on surface layers which might accumulate on the target because any such layer would be carbon itself. The use of fresh target spots and the short exposures needed for good elastically scattered groups avoided the contamination problem on the targets used for scattering.

In determining the position of a particle group on the plate, standard procedure for the broad-range spectrograph was used; that is, the point on the straight high-energy edge of the group at $\frac{1}{3}$ of peak height was used. This point has been shown to be quite insensitive to changes in target (or source) thickness. Other factors influencing group shape such as object size, magnification, and aberration were always the same for the two groups so that as far as these are concerned any point on the group could be used in determining the distance between closely spaced groups.

For ease in calculation the usual procedure was to use the calibration curve for the spectrograph that had been derived from polonium alpha groups, with the old value for the alpha energy. The energy of a given scattered group was found on this standard, the bombarding energy calculated and compared with the bombarding energy based on the $Li^7(p,n)Be^7$ threshold energy. The percentage difference found was applied to the assumed alpha energy and thus a new value for the alpha energy, based on the threshold, was found. As pointed out above, the result does not depend on knowing the absolute calibration of the spectrograph.

## IV. SPECIFIC EXPERIMENTAL METHODS

The methods described in the last section apply to all four of the independent procedures, now to be described, for comparing the alpha-particle energy with the threshold energy.

### A. Changing Spectrograph Field

The first method used for comparing the threshold energy with the alpha-particle energy required changing the spectrograph magnetic field. A lithium target was put in place, the threshold run with the proton beam, and then, with the input energy held essentially at the threshold value, (beam analyzer field constant) a thin gold target was substituted for the lithium. Protons scattered at 90 degrees to the beam were recorded on the spectrograph plate. The polonium source was then substituted for the gold target and the spectrograph field changed to put the alpha group at the same position as the proton group. Gold was used for the scatterer to minimize the change needed in the spectrograph field and to eliminate any uncertainty in scattering angle as an important consideration. In many runs protons scattered from other elements, including the lithium itself, were also recorded on the same plate with the same field settings. The positions of these groups were also used in the calculations.

A field change of a factor of 1.68 was required to superimpose the alpha group and the proton group scattered from gold. It was found that the energy ratio obtained depended on which group was recorded first, that is, on whether the spectrograph field was increased or decreased in going from one setting to the other. Clearly there is a differential hysteresis in the magnet so that the field along the particle trajectory does not have a linear relation to the field at the fluxmeter probe. Different parts of the spectrograph focal surface were used for recording the groups in the hope that the differential hysteresis might be less for, say, trajectories lying near the probe. The effect was observed in all cases, however, and amounted to about 0.2% in energy. A mean of an equal number of runs with increased and with decreased fields was taken for the result using this first method but less weight is placed on this value than on the results of the last two methods to be described because one does not expect the differential hysteresis effects to be linear.

### B. Changing Beam Analyzer Field

The differential hysteresis effect made it desirable to use a method for comparing the energies that would allow the spectrograph field to be kept constant throughout the measurements. To do this a particle group was

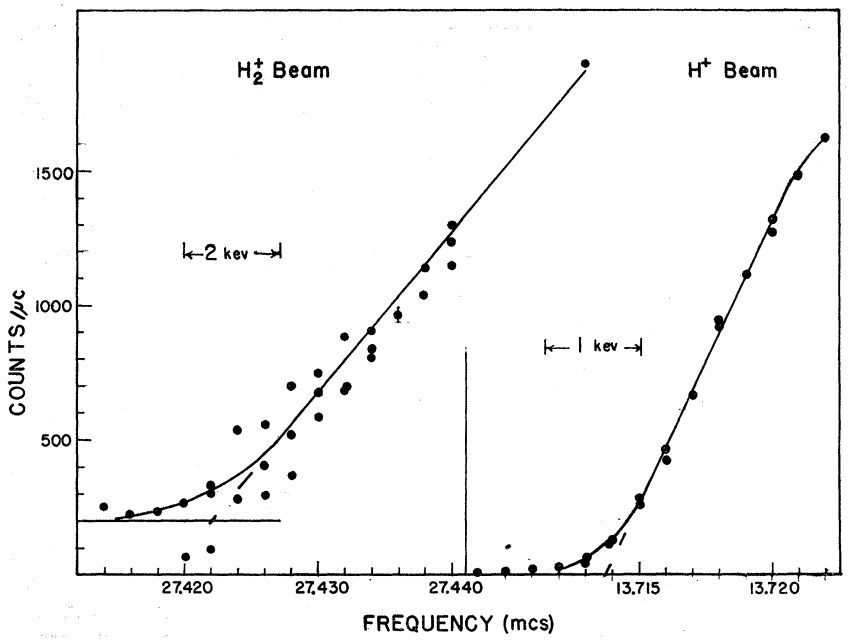


FIG. 2. Yield curves near threshold for the $Li^7(p,n)Be^7$ reaction taken with the molecular beam and the atomic beam. The abscissa scale is such that a given length represents the same energy difference in proton energy on the two plots.

needed which has the same magnetic rigidity as the polonium alphas and which has an energy of known ratio to the threshold. One way is to run the threshold with the proton beam and then to accelerate deuterons of an energy such that, when scattered from a suitable target at a certain angle, they have the magnetic rigidity of the alphas. The beam analyzing magnet may be used to compare the energy of the protons used for the threshold and the deuterons used for scattering.

When this method was tried it was again found that the result depended on whether the beam analyzer field was increased or decreased in going from one setting to the other. Again an average of "field up" and "field down" runs was taken. The result agreed with that of the first method but is also given less weight than the results of the following methods.

### C. Using Fixed Fields With Molecular Beam

To eliminate the uncertainty introduced by differential hysteresis, a comparison method was used that required no measurement of field ratios because both analyzer and spectrograph fields were held essentially constant throughout the experiment. The lithium threshold was run using the molecular hydrogen beam, then the accelerator ion source was switched to deuterium and the deuterons scattered from appropriate target materials at the proper angles to give scattered particles of the same magnetic rigidity as the polonium alpha-particle. As in the first two methods, the target was then replaced by the source and the alpha group superimposed on the deuteron group on the spectrograph plate. In principle the only quantities entering the calculation in this case are the masses of hydrogen ion, proton, deuteron, alpha-particle and target nucleus, and the scattering angle. In practice the two groups did not exactly coincide on the plate and the scattering was not done with exactly the threshold field in the beam analyzer. Hence, the dispersions of the analyzer and spectrograph enter but are known well enough so that over the small range used a negligible uncertainty is introduced. Again in this method it is vital that the source wire be exactly at the beam spot position. Several target nuclei and scattering angles were used, to give checks on scattering angle and possible target surface layers.

### D. Measurement of Q-values

In comparing the alpha-particle energies measured in different laboratories a source of discrepancy is the choice of the point on the observed energy distribution that is taken to represent the "true" particle energy from a source of zero thickness. Similarly discrepancies may arise, though perhaps to a lesser degree, in choosing the "true threshold" from the observed yield of neutrons versus bombarding energy. Since the primary reason for the present measurements was to compare the energy standards used by different laboratories in determining nuclear energies, it was decided to measure precisely some reaction energies against the polonium alpha energy by the standard methods used by owners of broad-range spectrographs and compare the results with those obtained by laboratories using the lithium threshold standard. Thus the standards would be compared in the manner in which they are actually used. As stated in the Introduction, only a few nuclear $Q$ values are suitable for this purpose.

In the present measurement of the $Mg^{24}(d,d')Mg^{24*}$ reaction both the elastically scattered and inelastically

scattered deuterons fell on the spectrograph plate with a given field setting. Deuterons elastically scattered from $Li^7$ at 90 degrees or from $B^{10}$ at 120 degrees had nearly the same energy as the inelastic group from $Mg^{24}$. Thus all magnetic fields could be kept constant and the ratio of energies of elastic to inelastic groups was found not only from the calibration curve but from known mass ratios and scattering angles.

The $N^{14}(d,p)N^{15*}$ $Q$ values were measured with the standard operating procedure for the spectrograph. One usual source of error, however, was not present because in every case the group of deuterons elastically scattered from $N^{14}$ occurred on the same exposure with the protons from the reaction. Thus the bombarding energy and output energy were found with one field setting of the spectrograph. The calibration curve was used in converting group position on the plate to particle momentum. Seven runs were made so that slight fluctuations in calibration should average out.

## V. RESULTS

Examples of threshold determinations with the atomic and molecular beams are shown in Fig. 2. Here neutron yield is plotted against the fluxmeter frequency of the beam analyzing magnet. The yield deviates from a straight line at the point expected for the target thickness used. The solid angle subtended by the counter in most runs should cause a deviation from linearity at about the same place. The "cusp" observed at threshold was considerably smaller in most cases than that expected from the geometrical resolution of the analyzer. This suggests that the energy stabilization of the accelerator was good enough to keep the beam centered on the exit slits of the analyzer most of the time so that the actual energy spread was less than that allowed by the geometry of the analyzer. If the stabilizer was manually overriden to cause the beam to stay mostly on one slit or the other, the threshold was seen to shift but by an amount less than the resolution. An attempt was made in all runs to allow the machine to find a stable equilibrium in energy and to leave the beam focussing and steering controls untouched during the threshold determination and subsequent scattering. Energy variations between threshold and scattering runs were felt to be less than the analyzer resolution. A check of the effect of resolution was made in two series of runs in which resolutions of 0.04, 0.08, and 0.16% were successively used, in each case a threshold and then a scattering being taken.[18a] No consistent effect was found. The observed differences lay within the resolutions and appeared to be random.

Figure 3 shows an example of alpha, deuteron, and proton groups (superimposed) on one exposure. The sources and targets used in these measurements were moderately thick in the sense that they were thick compared to the theoretical resolution of the spectrograph. Polonium sources used for calibrating broad-range spectrographs have invariably been of this type for regions of the focal surface near the 90-degree trajectory. Scattered particle groups also have energy spreads that are in general more than the theoretical resolution because of spread in energy of the input beam and (usually) target thickness. The groups shown in Fig. 3 were gotten using Methods A and B described above but illustrate the type of data obtained in all methods.

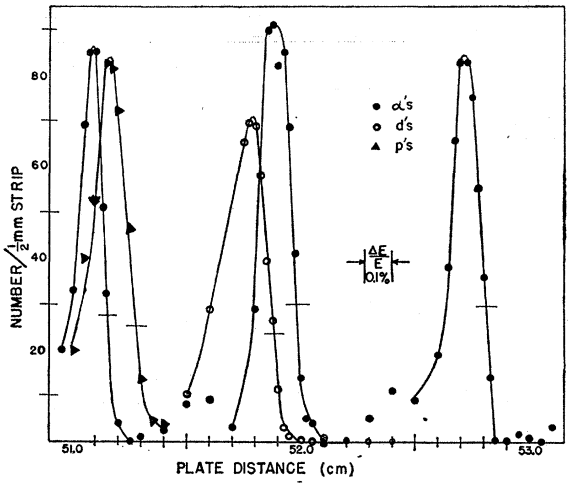


FIG. 3. Plot showing superposition of proton, deuteron, and alpha-particle groups on the spectrograph plate. The solid circles represent the number of alpha particles, open circles the number of deuterons, and the triangles the number of protons. The short horizontal bar at $\frac{1}{3}$ height of high-energy edges shows the point used to represent the group position.

It was thought that the fact that the source wire was round whereas the target spot was flat might cause an error so a test was made with a round source and one for which the front half of the wire was milled away to produce a flat surface. No change in energy was found.

Results from all runs are listed in Table IV according to the methods described above. For the first two methods the averages of "field up" and "field down" runs are shown and the mean of these carried to the last column which lists averages for each method. At the bottom of the last column the grand weighted average for all methods is given. This is 5.3086±0.003 Mev. All numbers are based on a value of 1.8811 Mev for the $Li^7(p,n)Be^7$ threshold. The result of this experiment gives the ratio of these two energies as 2.8221±0.0015. The errors shown in Table IV are discussed in the next section.

## VI. ERRORS

Sources of error include uncertainties in extrapolating the neutron yield to obtain the threshold frequency, differences in position of beam spot and polonium

[18a] *Note added in proof.* An additional run was made with the spectrograph object slit also reduced to $\frac{1}{4}$ mm. The upper edge of the slit remained at the position of the upper edge of the source wire. No change was found in the measured energy ratios.

TABLE IV. Energy of $Po^{210}$ alphas based on $Li^7(p,n)Be^7$ threshold = 1.8811 Mev.

| Method[a] | Results from individual runs (Mev) | | | | | | | Average |
|---|---|---|---|---|---|---|---|---|
| *A*. Atomic threshold, change spectrograph field | | | | | | | Av. | |
| Field up | 5.3030 | 5.3022 | 5.2017 | 5.3045 | 5.3025 | 5.3039 | 5.3030 | 5.3090±0.005 |
| Field down | 5.3163 | 5.3152 | 5.3177 | 5.3095 | 5.3160 | 5.3146 | 5.3149 | |
| *B*. Atomic threshold, change analyzer field | | | | | | | | |
| Field up | 5.3081 | 5.3098 | | | | | 5.3090 | 5.3076±0.005 |
| Field down | 5.3045 | 5.3079 | | | | | 5.3062 | |
| *C*. Molecular threshold, field constant | 5.3113 | 5.3074 | 5.3079 | 5.3142 | | | | 5.3102±0.003 |
| *D*. $N^{14}(d,p)N^{15*}$ [b] | 5.3087 | 5.3092 | 5.3036 | 5.3102 | 5.3139 | | | 5.3085±0.003 |
| *D*. $Mg^{24}(d,d')Mg^{24*}$ | 5.3094 | 5.3092 | 5.3044 | | | | | 5.3077±0.003<br>5.3086±0.003 |

[a] See text for description of methods *A* to *D*.
[b] Each entry is the weighted average of the three *Q* values used for comparison.

source, uncertainty in scattering angle, measurements of group position on the plate and conversion of group position to energy, field drifts during exposure, and surface layers on targets and sources. The estimated uncertainty for each of these and the corresponding error in the polonium alpha energy is listed in Table V with an indication of the comparison methods to which it applies. The error in threshold includes, as well as statistical factors, the uncertainty from resolution effects and deviation of the true yield near threshold from the assumed linear curve. When the molecular beam is used, there is broadening of the energy distribution caused by molecular vibrations. This has the same effect as decreasing the resolution of the beam analyzer and thus should cause a larger cusp in the yield curve near threshold. With the molecular beam, however, backgrounds were higher and statistical fluctuations larger so it was difficult to observe this effect. As shown in the table, a larger uncertainty was assigned to molecular thresholds than to atomic thresholds.

As noted in the section on methods, many checks were made on the beam spot position relative to the source wire, and as each exposure for an alpha group involved an independent measurement of source position the net error is small and random. Checks on the scattering angle have been discussed. The entry in the table is the largest uncertainty involved in any of the methods. The error assigned to Methods A and B is almost the entire differential hysteresis effect and is essentially a limit of error.

Surface layers on the lithium target would cause too high a threshold frequency to be found and a layer on the polonium wire would decrease the alpha-particle energy. Both would result in too low a value for the alpha energy. Fresh sources and target spots were used for each run and the result is the highest value yet found for the polonium-alpha energy so it seems quite unlikely that an appreciable error occurred from this source. A surface layer on the target used for scattering or for reactions would give too high a value for the alpha energy. Again fresh target spots were used for each run and, as mentioned earlier, carbon was usually one of the targets. Build-up of surface layers would have been seen through disagreement of input energy calculated from the groups scattered from carbon and from those scattered from other elements. No such discrepancy was seen and thus the effect of surface layers was considered negligible.

The major uncertainties are, for Methods A and B, the differential hysteresis and possible change in energy (within the resolution) between threshold and scattering; for Method C, the latter only; and for Method D, uncertainties in the calibration curve. These uncertainties cause different errors in each of the *Q*-value measurements so the table entry is only an example.

The over-all error of 3 kev given for the final result is not obtained by a straightforward propagation of errors but is intended to be a limit of error. The total

TABLE V. Summary of representative errors.

| Source of error | Error | Error in $Po^{210}$ alpha energy (kev) | Applies to method[a] |
|---|---|---|---|
| Threshold | | | |
| Atomic | ±0.01% (0.2 kev) | ±0.5 | *A*, *B* |
| Molecular | ±0.02% (0.8 kev) | ±1.1 | *C* |
| Source position | ±0.03 mm | ±0.3 | *A*, *B*, *C*, *D* |
| Scattering angle | ±0.03 degree | ±0.9 | *A*, *B*, *C*, *D* |
| Group position | ±0.1 mm | ±0.5 | *A*, *B*, *C*, *D* |
| Field drift | ±0.01% | ±0.5 | *A*, *B*, *C*, *D* |
| Differential hysteresis | ±0.1% | ±5.0 | *A*, *B* |
| Energy drift between threshold and scattering | ±0.08% | ±4.0 | *A*, *B*, *C* |
| Calibration curve | | ±3.0 | *D* |

[a] See text for description of methods *A* to *D*.

spread in the averages of the five measurements is only 2.6 kev, so the ±3-kev limit of error is generous.

## VII. DISCUSSION

Agreement of the five essentially independent methods of comparing the threshold with the alpha energy gives one considerable confidence in the present result in spite of the disagreement with earlier work. The result is in essential agreement with the latest previous work, that of White *et al.*[3] In this connection it might be noted that these authors used the position of the peak of the alpha-particle group to give the particle energy, whereas they state that the width of the ion group used for comparison was considerably smaller than the width of the alpha group shown. This would indicate that the alpha group width was determined by source thickness and not analyzer resolution. In this case, some point on the high-energy edge (such as the $\frac{1}{3}$ height of the distributions) rather than peak height position should be used to represent the group energy If a triangular distribution is assumed for their ion group and $\frac{1}{3}$ heights used, the polonium energy appears to be perhaps 1 kev higher than the value given. It is then in rather good agreement with the present result.

Most of the earlier work was of necessity done with much stronger sources than presently used. The attendant energy spread means that considerable uncertainties are introduced in choosing the point on the distribution which represents the particle energy for a monoenergetic source. With the spectrograph only a *comparison* of group positions is required and the question of which point represents the energy of the group is avoided. The question does arise in the threshold measurement. That is, does the extrapolated point correspond to the mean energy of the input beam? This question has the same effect for all methods used in the present experiment. It has been discussed at length in the section on methods. Here again the point should be emphasized that the present experiment seeks to compare the *nominal* $Li^7(p,n)Be^7$ threshold and $Po^{210}$ alpha energies as *actually used* for energy standards.

In the earlier comparison of the two energies[1] rather thick sources and rather old sources were used and these were washed with solvents which may have deposited more surface layers than they removed.

A resumé of the various determinations of the polonium alpha-particle energy is given in Fig. 4. In comparing the present result with absolute measurements one must keep in mind the value assumed for the $Li^7(p,n)Be^7$ threshold energy. If this energy is actually lower than the value used here, say 1.8808 Mev, as has been suggested[19] the present result will be lowered

[19] This suggested average includes recent results of G. C. Phillips and H. Staub which have been privately communicated.

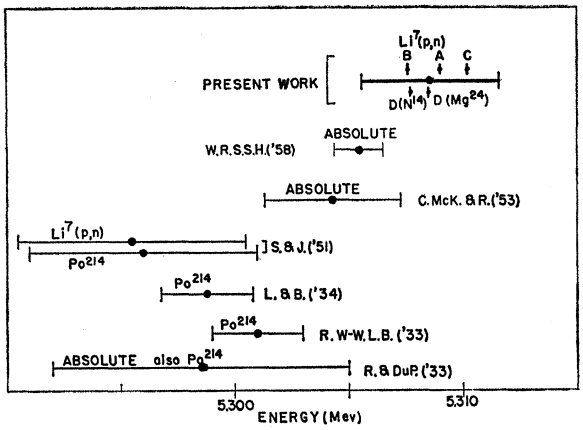


FIG. 4. Comparison of various determinations of the energy of alpha particles from $Po^{210}$. The label on each line representing a measurement gives the authors initials, year of publication, and energy standard used. See text for references. The results of the five measurements in the present work are shown by vertical lines above and below the line representing the average. They are labelled to correspond with the listing in Table IV. As stated in the text, it is felt that the determination of White *et al.* (labelled W.R.S.S.H.) should be raised about 1 kev.

to 5.3078±0.003 Mev. If the latest two previous determinations[2,3] are averaged with this number, counting it as five independent measurements and adjusting the result of White *et al.* as above, the result is 5.3071 Mev.[19a] This is 0.17% higher than the value used to calibrate the broad-range spectrographs used for so many nuclear reaction energy measurements. All values based on the older number should apparently be raised by about 0.17%.

It is of interest to re-examine the long-standing discrepancy between mass-spectrometer data and nuclear reaction data[20] in the light of this new value for polonium alpha-particle energy. Most of the precise nuclear reaction values for nuclei heavier than $O^{16}$ are based on the old polonium number, whereas many of the most precise values for nuclei lighter than $O^{16}$ are based on the $Li^7(p,n)Be^7$ threshold, directly or indirectly. The new polonium alpha energy will raise the masses above $O^{16}$ while making little difference in those below. This should tend to reduce the discrepancy with the mass spectrometer values.

[19a] *Note added in proof.* A new absolute measurement by A. Rytz gives 5.3048±0.0006 Mev. At the McMaster Conference on Nuclidic Masses it was suggested that a value of 1.8807 Mev be used for the $Li^7(p,n)Be^7$ threshold energy. The present work then gives 5.3075±0.0015 (probable error) Mev. The average of this, the Rytz value, the Collins *et al.* result and the adjusted result of White *et al.*, is 5.3056. It was suggested at the Conference that this number be used as a calibration standard.

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