This behavior was somewhat mysterious when the plasmon state was regarded as one of the states arising from the continuum. Now that we have traced its position onto the nonphysical sheet for $x>x_c$, this mystery is dispelled.

B. Terms in the Operator[21] θ

$$\theta_0[\tilde{K},\tilde{G}]=\tilde{K}\tilde{G},$$

$$\theta_1[\tilde{K},\tilde{G}]=\tfrac{1}{2}i\sum_{xyz}\left(\frac{\partial\tilde{K}}{\partial x}\frac{\partial\tilde{G}}{\partial p_x}-\frac{\partial\tilde{K}}{\partial p_x}\frac{\partial\tilde{G}}{\partial x}\right),$$

[21] The summation of xyz means that xyz are to replace each other cyclically. The double summation means that xp_y is to be replaced by each of the eight other combinations of a component of **R** and a component of **p**.

$$\theta_2[\tilde{K},\tilde{G}]=(\tfrac{1}{2}i)^2\Bigg[\sum_{xyz}\frac{1}{2}\left(\frac{\partial^2\tilde{K}}{\partial x^2}\frac{\partial^2\tilde{G}}{\partial p_x^2}+\frac{\partial^2\tilde{K}}{\partial p_x^2}\frac{\partial^2\tilde{G}}{\partial x^2}\right)+\sum_{xyz}\left(\frac{\partial^2\tilde{K}}{\partial x\partial y}\frac{\partial^2\tilde{G}}{\partial p_x\partial p_y}+\frac{\partial^2\tilde{K}}{\partial p_x\partial p_y}\frac{\partial^2\tilde{G}}{\partial x\partial y}\right)-\sum_{p_xp_yp_z}\sum_{xyz}\frac{\partial^2\tilde{K}}{\partial x\partial p_y}\frac{\partial^2\tilde{G}}{\partial y\partial p_x}\Bigg].$$

The full θ is given by

$$\theta[\tilde{K},\tilde{G}]=\lim_{R'\to R;\,p'\to p}\exp\left[\frac{i\hbar}{2}\sum_{xyz}\left(\frac{\partial}{\partial R_x}\frac{\partial}{\partial p_x'}-\frac{\partial}{\partial p_x}\frac{\partial}{\partial R_x'}\right)\right]\times\tilde{K}(\mathbf{R},\mathbf{p}\omega)\tilde{G}(\mathbf{R}',\mathbf{p}'\omega).$$

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Absolute Measurement of a Set of Energy Calibration Standards*

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A 180° magnetic spectrometer has been employed to measure the energy of several neutron thresholds and γ-ray resonances, as well as the energy of the alpha particles emitted by Po^{210}. The primary reason for performing these experiments was to obtain a set of energy standards with consistent experimental techniques for all the measurements. The neutron thresholds studied were $Li^7(p,n)Be^7$, $B^{11}(p,n)C^{11}$, $C^{13}(p,n)N^{13}$, and $F^{19}(p,n)Ne^{19}$. The γ-ray resonances at 872 kev in $F^{19}(p,\alpha\gamma)O^{16}$ and at 992 kev in $Al^{27}(p,\gamma)Si^{28}$ were observed. The same instrument used to make the energy measurements for these experiments was also employed to determine the energy of the alpha particles emitted by Po^{210}.

INTRODUCTION

Considerable effort has been devoted in recent years to precise energy measurements of several nuclear reactions frequently employed for calibration purposes. These measurements have consisted primarily of the energy determination of neutron thresholds, γ-ray resonances, and the measurements of the energy of alpha particles emitted by radioactive substances. Generally speaking, the reason for the continuous effort to obtain increased accuracy in these measurements has stemmed from the extensive use of these reactions in calibrating analyzing magnets associated with accelerator energy determinations and with Q-value and nuclear mass measurements. It seemed of some importance to perform a representative set of calibrations by employing a single instrument and a single analysis technique. This paper describes such a set of measurements.

The present work has been concerned with (1) the neutron thresholds in the reactions $Li^7(p,n)Be^7$, $B^{11}(p,n)C^{11}$, $C^{13}(p,n)N^{13}$, and $F^{19}(p,n)Ne^{19}$ and (2) the γ-ray resonances at 872 kev for the reaction $F^{19}(p,\alpha\gamma)O^{16}$ and at 992 kev for $Al^{27}(p,\gamma)Si^{28}$. In addition, (3) the energy of the alpha particles emitted by Po^{210} has been measured with the same instrument. These particular reactions were chosen as being those most frequently employed in energy calibration measurements.

EXPERIMENTAL PROCEDURE

The Rice University Van de Graaff accelerator, with associated 90° magnetic analysis, has served as the source of monoenergetic protons for these experiments, with a 180° magnetic spectrometer[1] employed to determine the proton energy. The basic procedure has been to determine the accelerator bombarding energy as a function of the magnetometer frequency of the Van de Graaff analyzing magnet by measuring the energy of

* Supported in part by the U. S. Atomic Energy Commission.
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[1] K. F. Famularo and G. C. Phillips, Phys. Rev. 91, 1195 (1953).

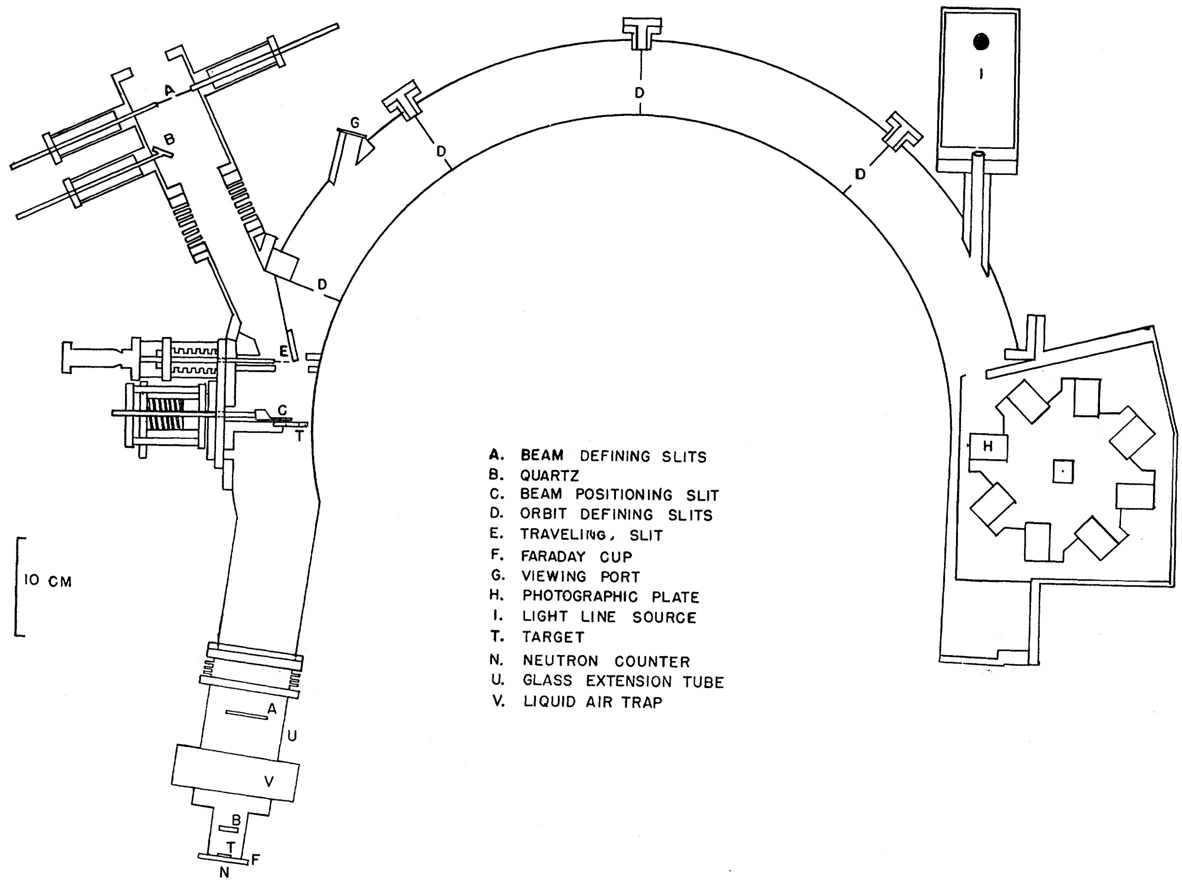

FIG. 1. The vacuum tube of the Rice University 180° magnetic spectrometer, including the extension tube added for these measurements. The radius of curvature of the system is approximately 35 cm. The solid angle defined by the slit system is about 2×10^{-4} steradian.

the protons scattered elastically from a C^{12} target located in the 180° spectrometer. This target could then be withdrawn from the beam and the bombarding protons would pass through the gap of the magnet and strike the second target located in a Faraday cup at the end of the extension tube. In this manner the bombarding energy was determined as a function of the frequency of the Van de Graaff magnetometer, while a neutron threshold or γ-ray resonance was simultaneously determined as a function of the same frequency. Figure 1 shows the vacuum tube of the spectrometer and the extension tube with its associated cold trap. The advantage in using the 180° spectrometer for the energy determination was the fact that field probings could be made at any position in its gap so that the magnetic field could be corrected for its small inhomogeneity. Similar measurements could not be made on the 90° Van de Graaff analyzing magnet.

The 180° magnetic spectrometer was thus employed as an absolute instrument, the radius of curvature and the magnetic field strength were known for each charged particle group. The radius of curvature measurement was made in two parts. (1) The distance ($2R_0$) between the target and a reference light-line exposed on the photographic plate was measured with two traveling microscopes and this distance compared to a standard meter bar in order to obtain an absolute number for the distance. (2) The distance (x_0) from the reference light line on the photographic plate to the leading edge of the particle group was measured with a second microscope. The radius of curvature for the particle group was then obtained from $\rho_0=\frac{1}{2}(2R_0+x_0)$. The magnetic field was measured with a proton moment magnetometer located at a standard position in the magnet gap. This frequency measurement was corrected for the small inhomogeneity of the field to obtain f_0, the frequency corresponding to the magnetic field acting on those particles detected on the photographic plate. The Appendix contains the equations employed to obtain the particle energies from the corresponding momentum measurement $f_0\rho_0$. The method employed to correct the magnetic field for its small inhomogeneity is also described in the Appendix.

The neutron detection was performed with a slow-neutron, paraffin-moderated, $B^{10}F_3$ proportional counter. This counter has been described by Bonner and Cook in their paper on counter-ratio measurements.[2] Care was taken to ensure that at all times the counter subtended a solid angle larger than the cone of emitted neutrons. The γ-ray measurements were made with a conventional 1 in.×1 in. NaI(Tl) crystal. The elastic protons were detected in the 180° spectrometer with Ilford E-2 photographic plates.

Neutron Threshold Experiments

Marion has recommended the adoption of three standard procedures for measuring threshold energies[3]: (a) Bombarding beams with the highest possible resolution should be used, (b) the neutron detector should intercept a solid angle larger than the emitted neutron cone for the entire energy range covered, and (c) the extrapolation procedure for determining the threshold energy should utilize a plot of $(\text{yield})^{\frac{2}{3}}$ versus bombarding energy. These recommendations have been adhered to in all the threshold measurements made. The beam resolution was always required to be greater than $R=2000$. The neutron counter normally intercepted at least $\frac{1}{4}$ the total sphere. Recommendation (c) was made on the basis of the predicted yield for s-wave neutron emission from a thick target. Figures 3–6, which show some representative data for the reactions studied herein, are seen to be plotted as a function of yield rather than $(\text{yield})^{\frac{2}{3}}$. However, investigations were made of all these data to ensure that the threshold energies deduced from these representations were the same as those obtained from a $(\text{yield})^{\frac{2}{3}}$ representation. The general implication of these results is in agreement with the work of Browne *et al.*,[4] who found that extrapolation over a small region above threshold of a plot of yield versus frequency gave the same threshold value as that resulting from the $(\text{yield})^{\frac{2}{3}}$ plot. This condition could not be expected to extend to measurements of neutron threshold which occur with lower cross sections than these studied, and which consequently would require extrapolation over a larger energy region.

Newson *et al.*[5] made a careful study of the effects of target thickness and beam resolution on the determination of the Li^7 neutron threshold. These authors reported that $R=2000$ introduced an error of about $\Delta E=-0.3$ kev with respect to the threshold value expected for $R=\infty$. Here R is the ratio of beam energy

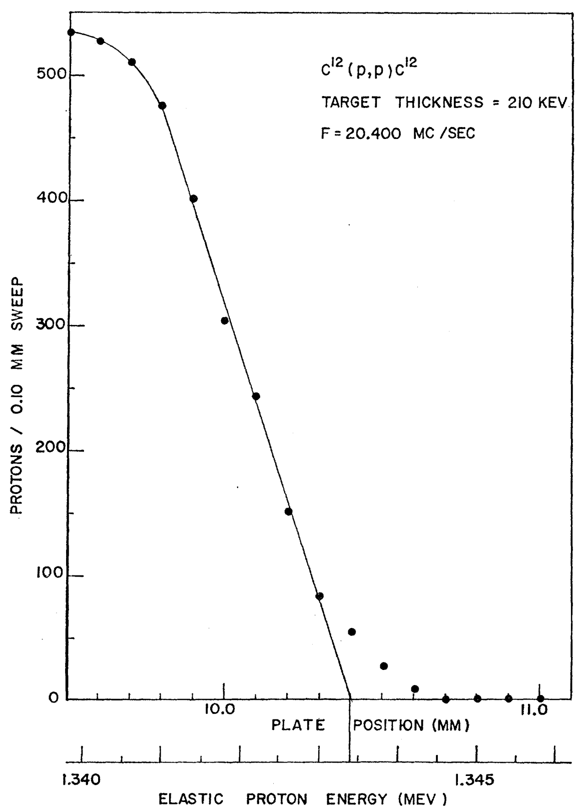

FIG. 2. Representative data obtained on the spectrometer photographic plates of the elastic protons from $C^{12}(p,p)C^{12}$. The energy scale indicates the sensitivity available in determining the energy of these protons.

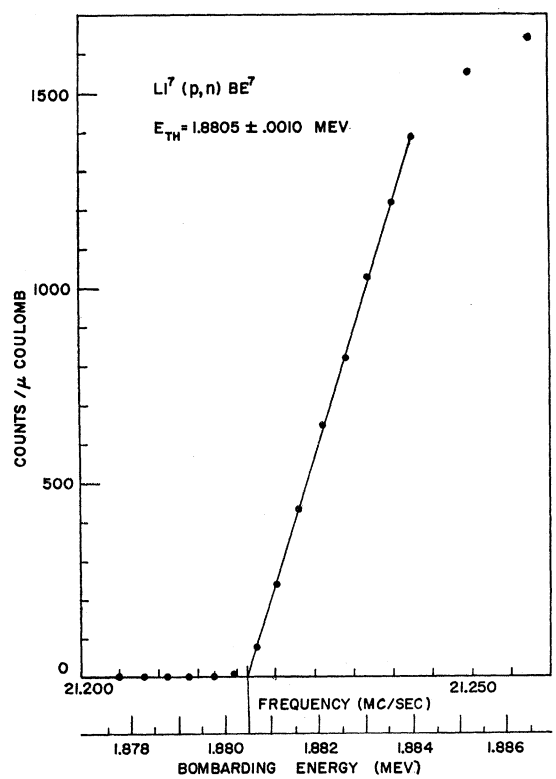

FIG. 3. Neutron counting data obtained from $Li^7(p,n)Be^7$. The energy sensitivity of this threshold is the highest of all the thresholds studied.

[2] T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954).

[3] J. B. Marion, *Proceedings of the International Conference on Nuclidic Masses*, edited by H. E. Duckworth (University of Toronto Press, Toronto, 1960), pp. 184–210.

[4] C. P. Browne, J. A. Galey, J. R. Erskine, and K. W. Warsh, Phys. Rev. **120**, 905 (1960).

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

to beam energy inhomogeneity. In addition their target thickness investigations showed that targets of about 5-kev thickness introduced a positive valued error of about the same magnitude as that resulting from $R=2000$. Consequently, the present experiments were performed with targets of about 5-kev thickness, since the beam resolution was generally about $R=2000$. The small errors due to these two effects could then be expected to cancel each other.

The measurements of bombarding energy were all performed using fresh, self-supporting C^{12} foils for the elastic scattering target. These targets were in general from 50 to 200 kev thick for the (p,p) reaction. Figure 2 shows the leading edge of the elastic proton group detected on the photographic plate, and indicates the energy sensitivity available in determining the elastic proton energy.

The second, threshold or resonance, target was always freshly prepared and protected from carbon buildup by the liquid nitrogen trap immediately in front of it. The average bombarding time for a threshold measurement was about one hour. Previous measurements on the $C^{13}(p,n)N^{13}$ threshold indicated that carbon buildup under these conditions was less than 0.1 kev.[6] Those measurements were made by using a carbon foil enriched to 69% C^{13} for the elastic target and simultaneously detecting the C^{13} neutron threshold from it. Since the elastic protons from both C^{12} and C^{13} could be detected on the same photographic plate, it was possible to compute the bombarding energy from the position of both groups of protons. This information accurately determined the amount of C^{12} that developed on the front of the target as a function of bombarding time.

$Li^7(p,n)Be^7$ Experiment

Figure 3 shows a representative display of the counting data for this threshold. The energy sensitivity is seen to be rather good. The experiment was performed using targets of enriched Li^7F evaporated on tantalum disks. The results of ten separate determinations of the threshold are shown in Table I. The accuracy of all the experiments was considered to be about the same so that no weighting factor was necessary.

TABLE I. The results obtained for the $Li^7(p,n)Be^7$ neutron threshold.

Experiment number	Threshold value (Mev)	Deviation (kev) from mean
1	1.8801	−0.4
2	1.8810	+0.5
3	1.8799	−0.6
4	1.8805	0
5	1.8810	+0.5
6	1.8795	−1.0
7	1.8815	+1.0
8	1.8806	+0.1
9	1.8803	−0.2
10	1.8806	+0.1
	Average = 1.8805	Average = ±0.45

Table II shows the error assignments made for each of various uncertainties present in the measurements associated with these experiments. There are six basic sources of error in these experiments, (1) the measurement of x_0, the distance from the leading edge of the particle group detected to the reference light line on the photographic plate, (2) the measurement of $2R_0$, the distance from the target to the reference light line, (3) the measurement of the field strength of the 180° spectrometer (frequency measurement), (4) the measurement of the field strength of the 90° Van de Graaff magnet, (5) the error associated with making the correction to $f_{180°}$ for the inhomogeneity of the 180° spectrometer, and (6) the error associated with making the threshold or resonance frequency assignment. There are, of course, small errors associated with the constants employed to make the energy calculations from the measured quantities $f_0\rho_0$ (see Appendix), but these are about an order of magnitude smaller than the six basic errors considered here.

For this threshold the rms error was ±0.55 kev, and the average deviation in the measurements was ±0.45 kev. The assigned error is ±0.8 kev so that these measurements yield the value 1.8805±0.0008 Mev for

TABLE II. Error assignments for the various errors present in these experiments.

Error source	Error in measurements (parts/10^5)						
	$Li^7(p,n)Be^7$	$B^{11}(p,n)C^{11}$	$C^{13}(p,n)N^{13}$	$F^{19}(p,n)Ne^{19}$	$F^{19}(p,\alpha\gamma)O^{16}$	$Al^{27}(p,\gamma)Si^{28}$	Po^{210} alphas
1. Measurement of x_0	3	3	3	2	5	5	7
2. Measurement of $2R_0$	6	6	6	6	6	6	6
3. Measurement of $f_{180°}$	10	10	10	12	8	8	6
4. Measurement of $f_{90°}$	6	6	6	6	6	6	0
5. Inhomogeneity correction for $f_{180°}$	5	7.5	7.5	7.5	3.3	3.3	7.5
6. Threshold assignment	6	7	7	7	10	5	0
Number of measurements	10	2	4	2	3	3	13
Sum error (kev)	1.22	2.20	2.32	3.30	0.61	0.60	2.80
rms error (kev)	0.55	1.00	1.07	1.50	0.27	0.27	1.38
Average deviation from mean (kev)	0.45	1.10	0.40	0.50	0.33	0.28	0.75
Maximum deviation from mean (kev)	1.00	1.10	0.80	0.50	0.52	0.41	1.60
Assigned error (kev)	0.80	1.50	1.50	2.00	0.50	0.50	1.50

[6] E. H. Beckner, M. A. thesis, Rice Institute, 1959 (unpublished).

TABLE III. Several of the more recent determinations of the $Li^7(p,n)Be^7$ neutron threshold energy.

Threshold energy (Mev)	Reference	Method
1.8822±0.0019	Herb *et al.*[a]	Absolute electric
1.8812±0.0019	Shoupp *et al.*[b]	Absolute velocity
1.8797±0.0011	Jones *et al.*[c]	Relative to Co^{60} γ ray
1.8814±0.0011	Jones *et al.*[c]	Relative to Au^{198} γ ray
1.8812±0.0009	Bondelid and Kennedy[d]	Absolute electric
1.8803±0.0005	Staub and Winkler[e]	Absolute magnetic
1.8805±0.0008	Present work	Absolute magnetic

[a] R. G. Herb, S. C. Snowden, and O. Sala, Phys. Rev. **75**, 246 (1949).
[b] W. E. Shoupp, B. Jennings, and W. Jones, Phys. Rev. **76**, 502 (1949).
[c] K. W. Jones, R. A. Douglas, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **94**, 947 (1954).
[d] R. O. Bondelid and C. A. Kennedy, Phys. Rev. **115**, 1602 (1959).
[e] H. A. Staub and H. Winkler, Nuclear Phys. **17**, 271 (1960).

the $Li^7(p,n)Be^7$ neutron threshold. This value is compared in Table III with those obtained by several other investigators.

$B^{11}(p,n)C^{11}$ *Experiment*

Figure 4 shows a representative display of the counting data for this experiment. The targets employed were enriched B^{11} evaporated on tantalum disks. Table II shows the error assignments made for the various uncertainties present. This threshold was measured twice, with an average deviation in the measurements of ±1.1 kev. The value obtained for the $B^{11}(p,n)C^{11}$ neutron threshold was 3.0164±0.0015 Mev.

$C^{13}(p,n)N^{13}$ *Experiment*

Figure 5 shows a representative display of the counting data for this experiment. The targets employed were enriched 69% C^{13} foils on tantalum disks. Table II shows the error assignments made for the various uncertainties present. This threshold was measured four times, with an average deviation in the measurements of ±0.4 kev. The value obtained for the $C^{13}(p,n)N^{13}$ neutron threshold was 3.2353±0.0015 Mev.

$F^{19}(p,n)Ne^{19}$ *Experiment*

Figure 6 shows a representative display of the counting data for this experiment. The targets employed were CaF_2 evaporated on tantalum disks. Table II shows the error assignments made for the various uncertainties present. This threshold was measured twice, with an average deviation in the measurements of ±0.5 kev. The value obtained for the $F^{19}(p,n)Ne^{19}$ neutron threshold was 4.2332±0.002 Mev.

γ-Ray Resonance Experiments

These two experiments were performed in order to include energy measurements below 1 Mev and to investigate the problems associated with resonance

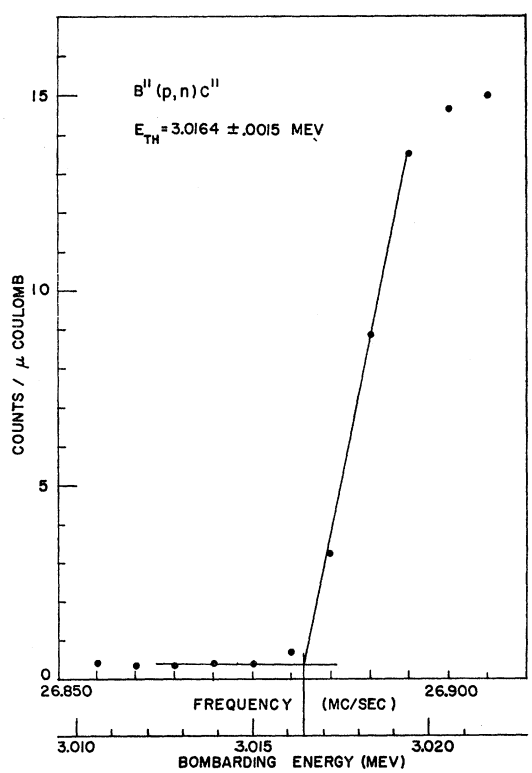

FIG. 4. Neutron counting data obtained from $B^{11}(p,n)C^{11}$.

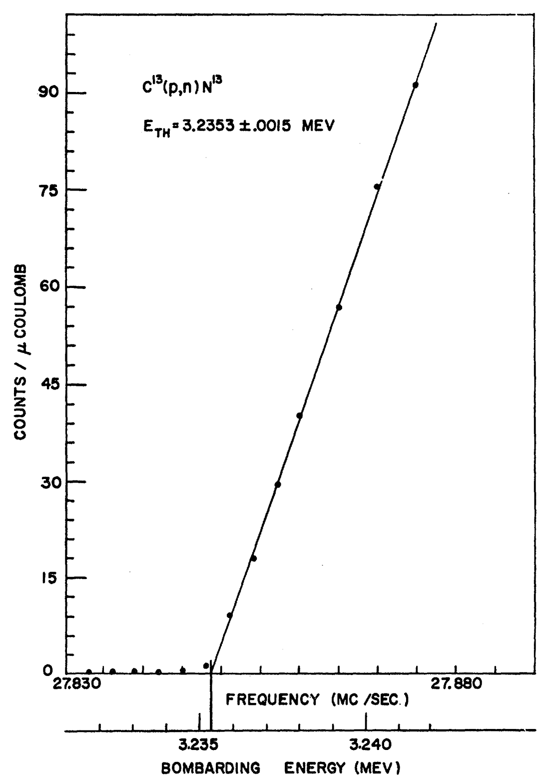

FIG. 5. Neutron counting data obtained from $C^{13}(p,n)N^{13}$.

calibration work. The main difficulty in making accurate resonance measurements originates in the fact that the measured width of a resonance results from two sources:

$$\Gamma_{\text{meas}} = (\Gamma_{\text{nat}}^2 + T^2)^{\frac{1}{2}}, \quad (1)$$

where Γ_{meas} = measured width of resonance, Γ_{nat} = natural width of resonance, and T = thickness of target employed. Fowler *et al.*[7] reported that when $\Gamma_{\text{nat}} \sim T$, the value of the observed resonant energy was affected. They determined that

$$E_{\text{true}}^R = E_{\text{meas}}^R - \tfrac{1}{2}T, \quad (2)$$

where E_{true}^R is the true resonant energy and E_{meas}^R is the measured resonant energy. Equation (2) indicates the necessity of knowing accurately the target thickness, but Eq. (1) shows that obtaining Γ_{meas} will not determine T unless Γ_{nat} is known.

Equation (2) does not obtain for the case $T \gg \Gamma_{\text{nat}}$. In this case E_{true}^R occurs at the energy corresponding to the half-height of the observed resonance. This fact suggests that γ-ray resonance experiments should employ thick targets if the resonant energy is of primary interest and Γ_{nat} is small. Recently Bondelid and Kennedy (see Table III, reference d) have developed methods for obtaining accurate measurements of Γ_{nat} as well as E_{true}^R from thick-target experiments even for cases of $\Gamma_{\text{nat}} \ll 1$ kev.

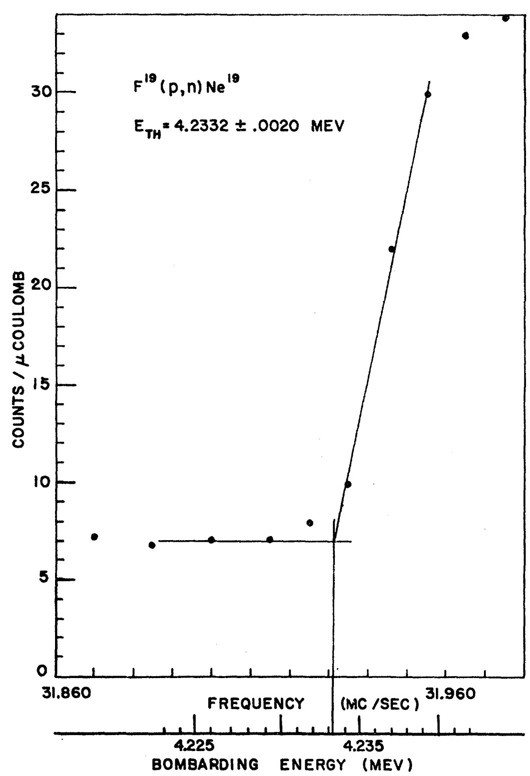

FIG. 6. Neutron counting data obtained from $F^{19}(p,n)Ne^{19}$.

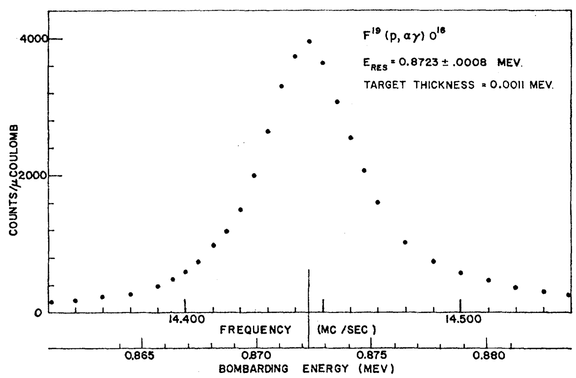

FIG. 7. γ-ray counting data obtained from $F^{19}(p,\alpha\gamma)O^{16}$, with a 1.13-kev thick LiF target. The energy scale has been offset 0.57 kev so that the center of the resonance corresponds to the true resonant energy.

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

This experiment was conducted in a manner which utilized Eqs. (1) and (2) for the determination of E_{true}^R. The value $\Gamma_{\text{nat}} = 4.5$ kev,[3] was employed to determine the target thickness and the true resonant energy obtained from Eq. (2). The targets employed were LiF evaporated on gold. Target thicknesses of from 1.1 to 5 kev were used for these experiments and were found to yield consistent results. Figure 7 shows the resonance obtained from the 1.1-kev target. The measured width in this case was 4.64 kev, which yields $T = 1.13$ kev for $\Gamma_{\text{nat}} = 4.5$ kev. The energy scale shown at the bottom of the figure has been offset $T/2 = 0.57$ kev, causing the center of the peak to indicate the true resonant energy. The resonance was examined three times, with an average deviation in the measurements of ± 0.33 kev. Table II shows the error assignment made for the uncertainties present in this experiment. The value obtained for this resonance in $F^{19}(p,\alpha\gamma)O^{16}$ was 872.3 ± 0.5 kev.

$Al^{27}(p,\gamma)Si^{28}$ *Experiment*

This experiment was performed utilizing "thick-target" techniques since the resonance possesses a natural width of 0.08 kev.[3] Figure 8 shows some of the data obtained. The targets employed were of aluminum evaporated on tungsten disks. Target thicknesses of from 3 to 20 kev were used and were found to yield E_{true}^R independent of T. For thick-target measurements the position of the true resonance energy is determined by the beam resolution. When the beam dispersion is much larger than Γ_{nat} ($\Delta E_{\text{beam}} = 0.5$ kev for this experiment), then the true resonance energy is located at the half-height position of the resonance. Table II shows the error assignments made for this experiment. The resonance was observed three times, with an average

[7] W. A. Fowler, C. C. Lauritsen, and T. Lauritsen, Revs. Modern Phys. 20, 236 (1948).

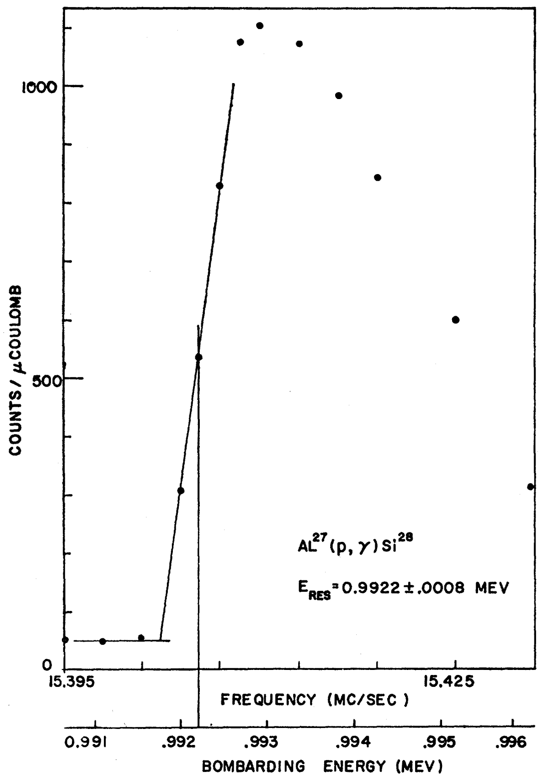

FIG. 8. γ-ray counting data obtained from $Al^{27}(p,\gamma)Si^{28}$. The assigned resonant energy is the energy found at half-height of the peak since $T \gg \Gamma_{nat}$ (see text). This experiment also gives an independent determination of the energy resolution of the bombarding protons, and is seen to yield $R \approx 2000$.

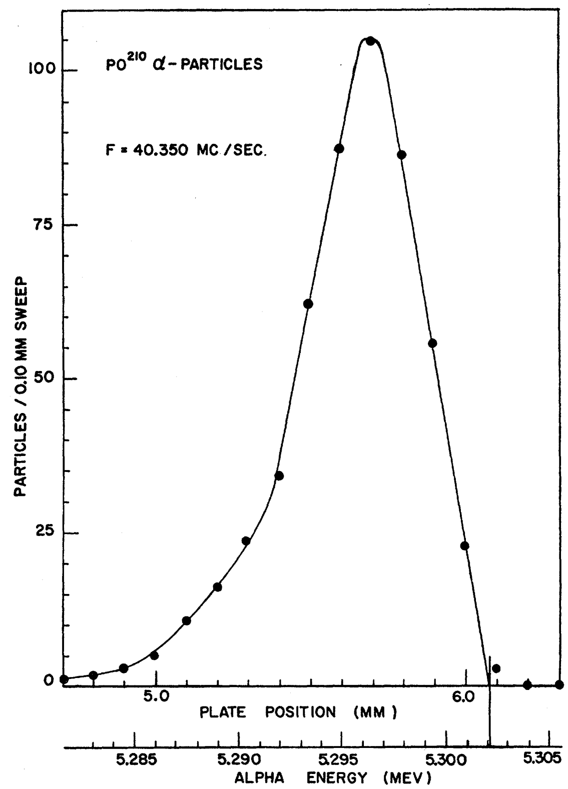

FIG. 9. Alpha-particle counting data obtained in a 20-minute exposure from a source prepared for 10 minutes in the Po^{210} solution.

deviation in the measurements of ± 0.28 kev. The value obtained for this resonance in $Al^{27}(p,\gamma)Si^{28}$ was 992.2 ± 0.5 kev.

ABSOLUTE MEASUREMENT OF THE Po^{210} ALPHA PARTICLES

The first accurate measurement of alpha particle velocity was made by Rutherford and Robinson in 1914.[8] By 1936, Briggs had made an absolute measurement of the energy of the alpha particles emitted by RaC′ to an accuracy of seven parts in 10^5.[9] Rytz recently reported the absolute measurement of the energy of alpha particles from several sources to an accuracy of about 11 parts in 10^5.[10] This is the highest accuracy reported since the work of Briggs for these alpha-particle energy measurements. Many relative measurements have been made using a wide variety of standards, the most common being RaC′ and one of the most recent the $Li^7(p,n)Be^7$ neutron threshold.[4] Despite the accuracy reported in the many measurements made since 1936, both absolute and relative, the energy values obtained for any given emitter are found to vary by almost 200 parts in 10^5. This surprising fact has been discussed by Asaro[11] and found to result primarily from the difficulty in obtaining a standard absolute measurement. The present measurements were made in order to assist in current efforts to arrive at a standard value for the energy of the alpha particles emitted by Po^{210}.

The 180° spectrometer was used to make these measurements. The source was inserted in the position previously occupied by the "elastic scattering" target. The energy measurements were accomplished using the equations contained in the Appendix to obtain the energy values from the momentum measurement $f_0\rho_0$.

The sources for these experiments were prepared by currentless-electrodeposition on pure silver foils using two slightly different techniques. (1) Nine sources were prepared by one of the authors (EHB) by dipping the source backings into the polonium solution for periods of from 2 to 10 minutes. These sources were used immediately after preparation in order to avoid the familiar problem of polonium diffusion into the backing.[12] This effect was observed in these experiments; a source five days old was found to yield an

[8] E. Rutherford and Robinson, Phil. Mag. **28**, 552 (1914).
[9] G. H. Briggs, Proc. H. Roy.Soc. (London) **A157**, 183 (1936).
[10] A. Rytz, Compt. rend **250**, 3156 (1960).
[11] F. Asaro, *Proceedings of the International Conference on Nuclidic Masses*, edited by H. E. Duckworth (University of Toronto Press, Toronto, 1960), pp. 223–227.
[12] I. I. Agpkin and L. L. Goldin, Bull. Acad. Sci. U.S.S.R. Phys. Ser. **21**, No. 7 (1957).

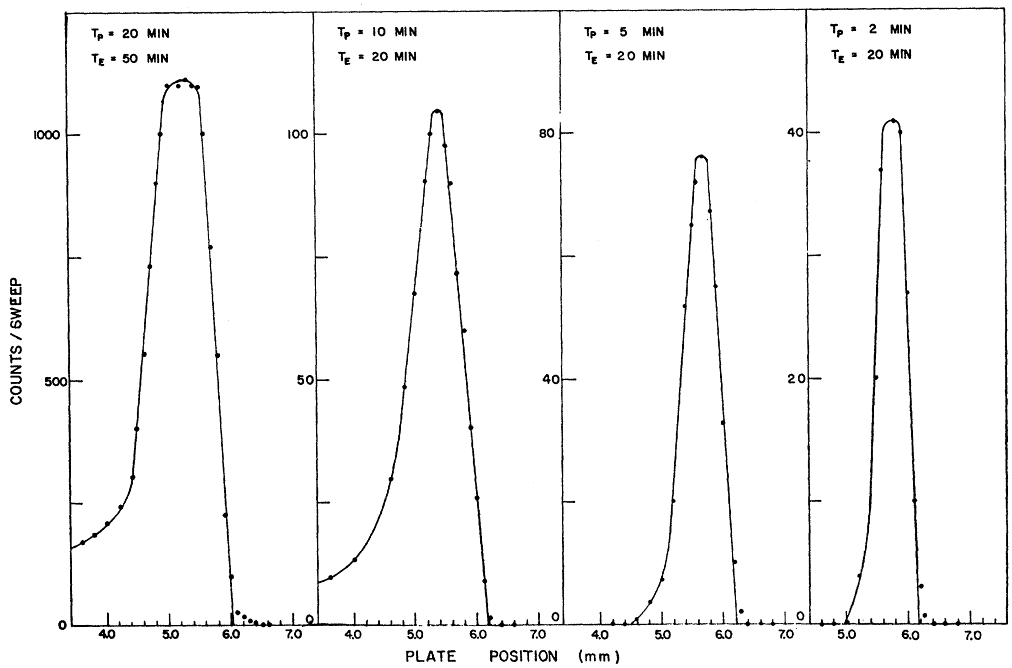

FIG. 10. Alpha-particle counting data obtained from several different sources. T_p is the time which the source backing was allowed to remain in the polonium solution. T_E is the exposure time of the spectrograph.

alpha energy 2 kev lower than the measured energy obtained from fresh sources. Several other sources were prepared by a second author (TAE) by a somewhat different technique. (2) These latter sources were prepared by placing a small amount of the polonium solution directly on the surface of the source backings. These sources were also used immediately after their preparation; in no case were sources more than six hours old employed for these measurements. Sources of various activities were employed by allowing the source preparation time to range from 2 to 20 minutes. Figure 9 shows a typical spectrum obtained from a source which was prepared for 10 minutes and exposed for 20 minutes. Figure 10 shows several spectra obtained from sources of varying thicknesses. These sources were exposed with the source defining slits set at 0.8-mm separation. In Fig. 10 the source preparation time is noted as T_p and the exposure time as T_E.

Source widths of from 0.1 to 0.8 mm were employed in these experiments with no detectable difference in the value of the measured energy. However, from the experiment performed with a slit width of 0.1 mm, it was possible to determine that the combined effects of the source thickness and the spectrometer resolution contributed about 3.5 kev to the measured width of the particle group. It was not possible to determine how much of this measured width was due to resolution effects of the spectrometer, so all that is known about the source is that it was less than 3.5 kev thick. This source was prepared for 2 minutes by the second method mentioned, and was the thinnest source employed in these experiments.

Thirteen determinations were made of the energy of the alpha particles emitted by Po^{210}, nine from sources prepared by method (1), and four from sources prepared by method (2). Table IV shows the results of these experiments, indicating the values obtained from the two types of sources as well as the source width employed. The average deviation in these measurements was ±0.75 kev, with no significant difference detected in the energy of the alpha particles obtained from the two types of sources. Experiments 8 and 9 were performed with the same source, but the source was held

TABLE IV. Results obtained in the measurement of the energy of the Po^{210} alpha particles.

Experiment number	Source prepared by	Preparation time (minutes)	Source width (mm)	Measured energy (Mev)
1	EHB	10	0.8	5.3022
2	EHB	10	0.8	5.3023
3	EHB	5	0.8	5.3041
4	EHB	5	0.8	5.3030
5	EHB	2	0.8	5.3010
6	EHB	2	0.8	5.3040
7	EHB	5	0.4	5.3026
8	EHB	5	0.4	5.3020
9	EHB	5	0.4	5.3017
		EHB average value:		5.3025
10	TAE	5	0.4	5.3021
11	TAE	10	0.4	5.3037
12	TAE	2	0.4	5.3018
13	TAE	2	0.1	5.3020
		TAE average value:		5.3024

TABLE V. The results of several recent measurements of the energy of the Po^{210} alpha particles.

Energy (Mev)	Reference energy	Reference
5.2988±0.0021	Po^{214} α particle $E=7.6804$ Mev	Lewis and Bowden[a]
5.3006±0.0026	Average value	G. H. Briggs[b]
5.3043±0.0029	Absolute	Collins *et al.*[c]
5.3054±0.0010	Absolute	White *et al.*[d]
5.2978±0.0015	Po^{214} α particle $E=7.6804$ Mev	Agpkin and Goldin[e]
5.3048±0.0006	Absolute	A. Rytz[f]
5.3086±0.0030	$Li^7(p,n)Be^7$ Neutron threshold$=1.8811$ Mev	Browne *et al.*[g]
5.3025±0.0015	Absolute	This work

[a] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 235 (1934).
[b] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).
[c] E. R. Collins, D. D. McKenzie, and C. A. Ramm, Proc. Roy. Soc. (London) **A216**, 219 (1953).
[d] F. A. White, F. M. Rourke, J. C. Sheffield, R. P. Schuman, and J. R. Huizenga, Phys. Rev. **109**, 437 (1958).
[e] See reference 12.
[f] See reference 10.
[g] See reference 4.

at an angle of 45° to the normal position for experiment 8 while being in its regular position for experiment 9. The purpose of these experiments was to test for the presence of surface contamination on the source. If contamination had been present, it would have appeared to be thicker to the alpha particles detected in experiment 8 than those detected in experiment 9, and the energy measured in the two cases would have been correspondingly different. The results of the experiments clearly show that no significant amount of surface contamination was present on the source.

The various error sources for these experiments are listed in Table II, along with the assigned values for the errors. The value obtained for the energy of the Po^{210} alpha particles was 5.3025±0.0015 Mev. Table V lists several of the more recent determinations of the Po^{210} alpha energy.

Examination of these various results shows that the work done with Po^{214} as reference energy yields low values for the Po^{210} alpha energy. This value for the Po^{214} alpha energy is that obtained by Briggs in 1936,[9] in which the reported experimental error was about 7 parts in 10^5. However, it would seem that this value of 7.6804 Mev for the Po^{214} alpha particles is inconsistent with the more recent measurements of the Po^{210} alpha particles. Rytz has recently measured the Po^{214} alpha particles and obtained a value of 7.6869±0.00075 Mev for their energy. Using this value for these alpha particles would result in considerable improvement in the agreement of the various experiments listed in Table V. Further improvement is obtained if a somewhat lower value for the Li^7 neutron threshold is used as the reference energy in the experiment of Browne *et al.*[4] Marion[3] has recommended the value 1.8807 Mev for this threshold, and employing this as the reference energy would lower the Browne *et al.* value for Po^{210} to 5.3075 Mev. However, a considerable discrepancy would still exist between the recent results of Browne *et al.* and the present work, with no reasonable explanation other than instrumental defects capable of accounting for the difference. In particular, the discrepancy cannot result from source preparation techniques, since one of the authors (TAE) visited the Notre Dame laboratory and prepared several sources by method (2) for comparison with the sources employed originally in the reported experiments. These comparison measurements[13] revealed no significant difference in the energy measured from sources prepared by Browne *et al.* and those prepared in a manner identical to method (2) as employed for experiments 10, 11, 12, and 13, reported herein.

TABLE VI. The results of all the experiments reported herein. The error assignments are those given in Table II.

Experiment	Measured calibration energy (Mev)
$Li^7(p,n)Be^7$	1.8805±0.0008
$B^{11}(p,n)C^{11}$	3.0164±0.0015
$C^{13}(p,n)N^{13}$	3.2353±0.0015
$F^{19}(p,n)Ne^{19}$	4.2332±0.0020
$F^{19}(p,\alpha\gamma)O^{16}$	0.8723±0.0005
$Al^{27}(p,\gamma)Si^{28}$	0.9922±0.0005
Po^{210} α particles	5.3025±0.0015

CONCLUSIONS

The primary purpose of these experiments was the performance of a number of calibration measurements under a set of consistent experimental conditions. All of the measurements had been made previously (some with higher accuracy than that obtained herein), but they had been conducted at a wide variety of laboratories and, consequently, employed various experimental procedures. It was not possible to know if consistent results could be expected to follow from these several measurements. Every possible effort has been made to employ consistent techniques in the present work, and it is believed that the results are as internally consistent as they could be made. Table VI shows the results of all the experiments performed. All the measurements are absolute insofar as the masses of the proton, alpha particle, and C^{12} nucleus are known absolutely. The measurements also require knowledge of the value of the gyromagnetic ratio and the charge-to-mass ratio of the proton, but these constants are known to accuracies of about 1 part to 10^5. The methods employed and the constants used in computing these energies are contained in the Appendix. The error assignments have been made on the basis of actual measurements whenever possible, with consideration given to the number of measurements made and the average deviation present in the results obtained. The error assigned to each reaction measurement has been in all cases larger than the calculated root-mean-square

[13] C. P. Browne (private communication, 1961).

error but smaller than a simple arithmetic sum of the errors present.

APPENDIX

The calculations of the energy of the charged particles detected with the magnetic spectrometer were made from the following formulas:

$$E_1=\left(\frac{M_2+m_2}{M_2-m_2}\right)^2 E_2, \text{ for elastic scattering at } 180° \text{ to incident particles,}$$

$$E_2''=A(f_0\rho_0)^2,$$

$$E_2'=E_2''-\Delta E_{\text{rel}},$$

$$E_2=E_2''-\Delta E_{\text{rel}}-\Delta E_\alpha,$$

with

$$\Delta E_{\text{rel}}=(E_2'')^2/2m_2c^2,$$

$$\Delta E_\alpha=\frac{2E_2'\alpha_0^2}{1+(m_2+M_2)(E_2'/m_1m_2E_1)^{\frac{1}{2}}},$$

and

$$A=\frac{2\pi^2z^2}{10^{14}\gamma_p^2}\left(\frac{m_p}{m_2}\right)\left(\frac{e}{m}\right)_p.$$

Here f_0 = proton magnetometer frequency, with the Hartree correction[14] included for inhomogeneity of field; ρ_0 = radius of curvature of particle $m_2=\frac{1}{2}(2R_0+x_0)$; ΔE_{rel} = first order relativistic correction; and ΔE_α = correction required due to detection of particle m_2 being made at the angle $(\pi-\alpha_0)$ rather than π. Also E_1 = bombarding energy of particles m_1, E_2 = energy of detected particles m_2, m_1 = nuclear mass of bombarding particles, m_2 = nuclear mass of detected particles, M_2 = nuclear mass of target nucleus, z = atomic number of detected particle, γ_p = gyromagnetic ratio of proton, m_p = mass of proton, and $(e/m)_p$ = charge-to-mass ratio of proton. The constants employed for these calculations were:

$$\gamma_p=(2.67523\pm0.00004)\times10^4 \text{ radians/sec gauss,}^{15}$$

$$(e/m)_p=(9.57946\pm0.00007)\times10^3 \text{ emu/g,}^{15}$$

$$m_p=1.007596\pm0.00001 \text{ amu,}^{16}$$

$$m_{\text{He}^4}=4.002775\pm0.000002 \text{ amu,}^{16}$$

$$m_{\text{C}^{12}}=12.000510\pm0.000005 \text{ amu.}^{16}$$

In determining f_0 for these calculations, the Hartree correction[14] made to the measured frequency was $\Delta f=\frac{1}{2}\int_0^\pi\Delta f(\theta)\sin\theta d\theta$, where the target was located at $\theta=0°$ and the detector at $\theta=180°$. The magnetic field was measured at 15° intervals to obtain $\Delta f(\theta)$ for the determination of this correction. The field was also measured inside the vacuum tube, and compared with the field measured at that position when the tube was not present, in order to determine that the copper vaccum tube did not affect the magnitude of the magnetic field. These measurements were made to an accuracy of 1 part in 10^4 in energy and revealed that the vacuum tube produced no field change to that accuracy.

[14] D. R. Hartree, Proc. Cambridge Phil. Soc. **21**, 746 (1923).

[15] E. R. Cohen, K. M. Crowe, and J. W. M. DuMond, *Fundamental Constants of Physics* (Interscience Publishers, Inc., New York, 1957), pp. 266–269.

[16] A. H. Wapstra, Physica **22**, 378 (1955).