Comparison of Alpha-Particle Energies from Po^{210} and Po^{214} and the Energy of Po^{210} Alpha Particles*

CORNELIUS P. BROWNE
University of Notre Dame, Notre Dame, Indiana
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The energies of alpha particles emitted by Po^{210} and Po^{214} were compared with a broad-range spectrograph. Techniques were the same as those used in a recent comparison of the Po^{210} alpha-particle energy with the $Li^7(p,n)Be^7$ reaction threshold energy. The result agrees with other measurements, and, thus, the discrepancy between the Po^{210} alpha-particle energy measured against the Briggs value for Po^{214} and the Po^{210} alpha-particle energy measured absolutely or against the $Li^7(p,n)Be^7$ threshold remains. If Rytz's recent absolute value for the Po^{214} energy is used the discrepancy disappears. A summary of all measurements shows that the energy of alpha particles from Po^{210} is very close to 5.3045 Mev.

I. INTRODUCTION

THIS work is part of a re-examination of energy standards for use in nuclear reaction measurements. A large part of the measurements of nuclear reaction energies is based on the threshold energy for the $Li^7(p,n)Be^7$ reaction whereas another large part of these measurements is based on the energy of alpha particles emitted by Po^{210}. Recent absolute measurements of this alpha-particle energy and measurements of the ratio of the two energies showed a discrepancy with the earlier results. This stimulated a number of people to make more measurements of both standards and of energies of related reactions.

A summary of the more recent determinations of the $Li^7(p,n)Be^7$ reaction threshold energy appears in a report by Beckner *et al.*[1] of some recent measurements of calibration standards. A review of all determinations was made by Marion[2] and a recommended "best value" (1.8807 Mev) chosen to be used as the primary calibration point for nuclear reactions. The agreement of the various measurements is quite good and it is felt that the uncertainty in the "best value" is ±0.4 kev or $\pm0.02\%$.

If one accepts this as the primary standard but wishes to use Po^{210} as a secondary standard, it is necessary to know the ratio of the two energies to high precision. This ratio may be found by direct measurement, or from absolute measurements of the Po^{210} energy, or from measurement of the Po^{210} energy based on some other absolute measurement. There are four recent absolute determinations of the Po^{210} alpha-particle energy. Here again the agreement is quite good and the weighted mean of the values should be good to within 0.9 kev.

The ratio of the mean values of the absolute measurements of the Po^{210} alpha-particle energy and $Li^7(p,n)Be^7$ threshold energy may then be compared with the ratio gotten from direct measurement. Such a measurement was made recently by Browne *et al.* In the report of this work[3] it is suggested that an earlier result of Sturm and Johnson[4] may have been influenced by aging effects in the Po^{210} sources. The most recent work of Beckner *et al.*[1] constitutes a measurement of the ratio inasmuch as both the alpha energy and threshold energy were measured on the same instrument in the one experiment. The result is lower than that of Browne *et al.*[3] but the spread is within the sum of the quoted uncertainties. The average of these two latest "ratio" measurements when multiplied by the "best value" for the threshold energy gives a result for the Po^{210} energy in excellent agreement with the mean of the absolute Po^{210} energy measurements.

Discrepancies appear when comparisons of the mean value of the absolute measurements of the Po^{210} energy are made with the value based on the measurement by Briggs[5] of the Po^{214} alpha-particle energy. The quoted uncertainty on this measurement is very small and for a long time the best value for the Po^{210} energy appeared to be the one based on this result. The discrepancy may, of course, arise either in the measurement of the ratio of the alpha-particle energies from Po^{210} and Po^{214} or from the absolute determination of the Po^{214} alpha energy. In view of the very small uncertainty given for the latter measurement by Briggs[5] it seems appropriate to re-examine the ratio measurements.

At the time the present work was begun at least four precise measurements had been made over a period of 28 years and the agreement was good. It was thought to be important, however, to measure the ratio with the same source preparation techniques and the same instrument used for the comparison of Po^{210} and the $Li^7(p,n)Be^7$ threshold energy. Among other things any systematic error in ratio measurements made with the broad-range spectrograph might be discovered. The result of this measurement, a summary of the ratio measurements, discussion of a recent absolute determination of the Po^{214} alpha-particle energy and a comparison of values for the Po^{210} alpha-particle energy obtained in various ways are given below.

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[1] E. H. Beckner, R. L. Bramblett, G. C. Phillips, and T. A. Eastwood, Phys. Rev. **123**, 2100 (1961).

[2] J. B. Marion, Revs. Modern Phys. **33**, 139 (1961).

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

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

[5] G. H. Briggs, Revs. Modern Phys. **26**, 1 (1954).

TABLE I. Measured energy of alpha particles from Po^{210} based on Po^{214} alpha energy of 7.6804 Mev.

Run	Deuteron bombarding energy[a] (Mev)	Target nuclei	Measured energy of alphas (Mev)
1	3.8909	Au, B^{10}, B^{11}	5.3035[b]
2	3.7546	Au, B^{10}, C^{12}	5.2964
3	3.8928	Au, B^{10}, C^{12}, O^{16}	5.3008
4	3.8845	Au, $Be^9(80°)$, $Be^9(90°)$, C^{12}	5.2986
5	3.8824	Au, $Be^9(80°)$, $Be^9(90°)$	5.2969
		Weighted mean	5.2985±0.0015

[a] Calculated from particles elastically scattered off gold.
[b] Given one quarter weight in average because of magnetic field cycling.

II. PROCEDURE

A broad-range spectrograph was used to compare the energies of the alpha-particle groups from Po^{214} and Po^{210}. The range of the spectrograph allowed both particle groups to be focussed on the nuclear-track plate with one setting of the magnetic field. The momentum ratio of the two groups was found, not from the calibration of the spectrograph, but from the position of groups of deuterons of a given incident energy scattered from various target materials. It was possible to carry out the entire measurement without changing the magnetic field. Thus differential hysteresis effects were avoided.

In each run deuterons were scattered from gold to give a group on the plate near the alpha-particle group from Po^{214}. To give groups near the alpha-particle group from Po^{210} the same deuteron beam was scattered from beryllium, boron, carbon, or oxygen at angles of 90 or 80 deg. Two or three deuteron groups were placed near this alpha group in each case, usually with a group on either side so that an interpolation could be made. For ease in calculating, the procedure was to assume a value for the momentum of alpha particles from Po^{214}, measure the small distance between this alpha group and the deuteron group scattered from gold and, using the known dispersion of the spectrograph, calculate the momentum of the deuterons. The deuteron input energy could then be found and from this the momentum of deuterons scattered from the lighter element. The measured distance from the second scattered deuteron group to the alpha group from Po^{210} and the known dispersion of the spectrograph allowed the momentum of these alphas to be found.

The procedure for making Po^{210} sources and mounting them at the position of the beam spot on the target was identical to the standard procedure used for calibrating the spectrograph and for the comparison of the alpha energy with the $Li^7(p,n)Be^7$ threshold energy.[3] All sources were made within a few hours of the time they were used except the source for the last run which was used on the second day after it was made.

The Po^{214} sources were made by collecting recoil atoms on a silver wire placed in radon gas. The wire was the same as the wires used for Po^{210} sources, i.e., $\frac{1}{2}$ mm. diam. The activity of the radon was about 1 mC and the wire was exposed for about 20 min with 200 v between the wire and the container. Stronger sources were obtained when a fraction of an atmosphere of air or CO_2 was mixed with the radon. The deposition chamber was arranged so that the wire could be withdrawn through an air lock and as a precaution the radon was frozen out in a liquid nitrogen trap before the wire was withdrawn. The Po^{214} source was mounted in the same way as the Po^{210} source.

III. RESULTS

Six runs were taken over a period of about a year. A plot of the particle groups recorded in one run is shown in Fig. 1. Here a group of deuterons scattered from gold lies near the alpha-particle group from the Po^{214} source, and deuteron groups scattered from Be^9 at 80° and 90° respectively lie on either side of the alpha-particle group from Po^{210}. Targets having a stopping many times the resolution were used for scattering so the deuteron groups are wide. The sources were thin but most of the group width still arises from source thickness. The usual procedure of taking the point on the high-energy edge at $\frac{1}{3}$ maximum to represent the position of the group was used.

Table I is a summary of the data obtained from the five runs used for the final average. The sixth run was discarded because of uncertainty in the position of the Po^{214} source. The first run was given one quarter weight because the elastic scattering was done at a different time from the source exposures and the magnetic field was cycled in between. All values in the table are based on the Briggs[5] value of 7.6804 Mev for the alpha-particle energy from Po^{214}. The ratio of the two energies, which is the quantity actually measured here, is 1.4495±0.0004.

The listed uncertainty is based mainly on the internal consistency of the results because estimated errors from source position uncertainty, counting and plotting

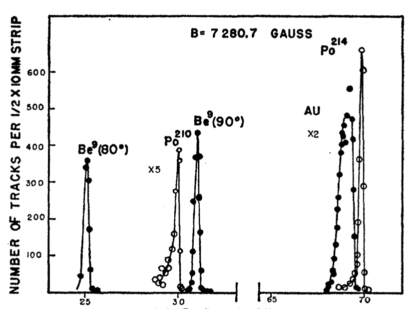

FIG. 1. Particle groups used in comparing the energies of alpha-particles from Po^{214} and Po^{210}. All groups recorded on one plate with a constant magnetic field. The open circles represent alpha-particles and the solid circles represent deuterons. The alpha groups are labelled with the symbol of source. The deuteron groups are labelled with the symbol of the scattering nucleus. Note the break in the abscissa scale.

errors, scattering angle uncertainty and field fluctuation are all smaller than the observed deviations of the results. The resolution of the beam analyzer would allow fluctuations of the order of those observed although experience has shown that over the short periods required for the elastic scattering runs the actual energy stability is usually better than that calculated from the resolution. It seems reasonable to consider the observed deviations as random and treat the stated uncertainty as the standard error.

IV. COMPARISON OF RESULTS

Ratio of Po^{214} Energy to Po^{210} Energy

The present result is compared, in Table II, with other measurements of the ratio of the energies of alpha particles emitted by Po^{214} and Po^{210}. In taking a weighted average of the ratio values a weight was assigned equal to the reciprocal of the stated uncertainty. This is the procedure used by Marion[2] in reviewing the $Li^7(p,n)Be^7$ threshold measurements. Where two absolute values were combined to give a ratio, an estimate of the uncertainty was made based on the stated uncertainties in absolute values. It is apparent from the table that the agreement is very good indeed. Measurements made over a period of 28 years in five laboratories are in complete agreement.[6] The listed standard deviation in the weighted mean corresponds to 0.5 kev in the Po^{210} alpha-particle energy, or 0.01%. Certainly the ratio of these energies is known to high precision.

Comparison of Po^{210} Alpha Energy Determined in Various Ways

It is instructive to compare the values for the energy of alpha particles from Po^{210} obtained in various ways namely: (a) by absolute measurement; (b) with respect to the $Li^7(p,n)Be^7$ threshold; and (c) with respect to the Po^{214} alpha energy.

A summary of the absolute determinations including the latest work of Beckner *et al.*[1] is shown in Table III.[7] Again a weighted average has been taken with weights assigned inversely proportional to the listed uncertainties. The value of White *et al.*[8] has been adjusted upward by 1 kev following an earlier suggestion.[3] Here again the agreement of the values is excellent and the deviations from the mean are consistent with the stated errors. Measurements over many years and in several laboratories agree. The weighted average is 5.3045 ± 0.0009 Mev. Surely this value may be considered known. The question then arises of the consistency of this result with that obtained from the energy ratio to the "primary standard" $Li^7(p,n)Be^7$ reaction threshold and with the result obtained from the energy ratio to the precisely-measured Po^{214} alpha energy.

Two direct measurements of the ratio to the $Li^7(p,n)Be^7$ threshold have been reported[3,4] and the recent absolute measurements of Beckner *et al.*[1] provide a third ratio. These three numbers are included in Table IV. Each of the values for the ratio has been multiplied by the adopted threshold energy of 1.8807 Mev to give the number listed in the third column. It is seen that there is a wide spread in the results. It was stated above that the Sturm and Johnson[4] result probably suffered from source age. The other two results differ by 4.4 kev where the standard errors are about 1.5 kev. This is a bit larger spread than one likes but not unreasonable in view of the stated uncertainties. The average of these two later results is 5.3053 ± 0.0022 Mev in excellent agreement with the average of the absolute measurements.

TABLE II. Ratio of the energy of alphas from Po^{214} to the energy of alphas from Po^{210} determined by various authors.

Authors	Year	Ratio
Rutherford *et al.*[a]	1933	1.44883 ± 0.00055
Lewis and Bowden[b]	1934	1.44946 ± 0.00055
Collins *et al.*[c]	1953	1.44927 ± 0.00082
Agapkin and Goldin[d]	1957	1.44973 ± 0.00082
A. Rytz[e]	1961	1.44905 ± 0.00027
This work	1961	1.44954 ± 0.00040
	Weighted mean	1.44925 ± 0.00013

[a] E. Rutherford, C. E. Wynn-Williams, W. B. Lewis, and B. V. Bowden, Proc. Roy. Soc. (London) **A139**, 617 (1933).
[b] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 235 (1934).
[c] Ratio of absolute values used. E. R. Collins, C. D. McKenzie, and C. A. Ramm, Proc. Roy. Soc. (London) **A216**, 216 (1953).
[d] Measured against Ra^{224} and Briggs ratio for Ra^{224}/Po^{214} used. I. I. Agapkin and L. L. Goldin, Bull. Acad. Sci. U.S.S.R. Phys. Ser. **21**, 911 (1957).
[e] Ratio of absolute values used. See text reference 7.

TABLE III. Summary of absolute measurements of Po^{210} alpha-particle energy.

Authors	Year	Energy (Mev)
Rosenblum and DuPouy[a]	1932	5.2985 ± 0.0065
Collins *et al.*[b]	1953	5.3043 ± 0.0029
White *et al.*[c]	1958	5.3064 ± 0.0010
A. Rytz[d]	1961	5.3048 ± 0.0006
Beckner *et al.*[e]	1961	5.3025 ± 0.0015
	Weighted mean	5.3045 ± 0.0009

[a] S. Rosenblum and G. DuPouy, Compt. rend. **194**, 1919 (1932); S. Rosenblum and G. DuPouy, J. phys. radium **4**, 262 (1933).
[b] See reference b, Table II.
[c] See text reference 8. Value raised 1.0 kev. See text.
[d] See text reference 9.
[e] See text reference 1.

[6] *Note added in proof*. W. B. Lewis has pointed out that the first two values listed in Table II do not represent two independent measurements and should not both be included in the weighted mean. If the first value is discarded the agreement is even better. The weighted mean is then 1.44934 ± 0.00012. This makes no change in the final result of this paper.

[7] *Note added in proof*. Another absolute measurement of this energy was just reported (A. Rytz, H. H. Staub, and H. Winkler, Helv. Phys. Acta **34**, 960 (1961). The result of 5.30493 Mev agrees with the average given here. But although these authors emphasize the importance of source condition they used only one thick contaminated source and include no estimate of errors arising from source properties. The good agreement of their result perhaps indicates that source condition is *not* so critical.

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

TABLE IV. Comparison of the alpha-particle energy from Po^{210} determined in various ways.

Method	Authors	Values (Mev)	Average (Mev)
Absolute	see Table III		5.3045±0.0009
vs $Li^7(p,n)Be^7$, $E_{th}=1.8807$ Mev	Browne *et al.*[a]	5.3075 ±0.0015	
	Beckner *et al.*[b]	5.3031 ±0.0015	5.3053±0.0022
	Sturm and Johnson[c]	5.2943[d]±0.0050	
vs Po^{214}, $E=7.6870$ Mev	Rytz[e]	5.3043 ±0.0005	
vs Po^{214}, $E=7.6804$ Mev	Briggs[f]	5.2997 ±0.0006	5.3020±0.0023
		Weighted mean	5.3043±0.0006

[a] See text reference 3.
[b] See text reference 1.
[c] See text reference 4.
[d] Omitted from average. See text.
[e] See text reference 9.
[f] See text reference 5.

If one looks only at the above results the energy of alpha particles from Po^{210} appears very well known and this energy and the $Li^7(p,n)Be^7$ threshold energy give consistent energy calibration points.

A discrepancy appears when these values for the Po^{210} energy are compared with the older value based on the precise measurement of the Po^{214} energy made by Briggs.[5] With the recent work of Rytz,[9] however, the picture changes radically. The Briggs[5] and Rytz[9] numbers for the Po^{214} alpha energy differ by 6.6 kev, although the stated uncertainties are only 0.9 and 0.7 kev, respectively. Thus it appears that the Po^{210} energy is now actually much better known from the absolute measurements, or even from the ratio measurements with the $Li^7(p,n)Be^7$ threshold than from comparison with Po^{214}. It would be better to use the value for Po^{210} obtained from absolute measurements and by comparison with the $Li^7(p,n)Be^7$ threshold, in combination with the well determined energy ratio to Po^{214}, to derive the Po^{214} alpha energy.

These points are illustrated by Table IV. The average of the absolute measurements, the average of the values derived from the $Li^7(p,n)Be^7$ threshold energy, and the value derived from the Rytz measurement of Po^{214} alpha energy using the well determined energy ratio, are seen to be in almost perfect agreement. It is only the value derived from the Briggs measurement of the Po^{214} energy that disagrees. The average of the values based on the Rytz and Briggs measurements of the Po^{214} energy is listed because there is no justification to weight one measurement more than the other. This average is still in fair agreement with the mean of the absolute measurements. The final weighted mean of the average values from the three types of measurement is 5.3043±0.0006 Mev. In deriving this number the three values were weighted inversely as the squares of the listed uncertainties because these are considered to be standard deviations.

If one accepts the facts that the absolute value of the alpha-particle energy of Po^{210} is known to better than 0.02%, the ratio of this energy to the energy of alphas from Po^{214} is known to 0.01%, and the absolute value of the $Li^7(p,n)Be^7$ threshold is known to 0.02%, it seems that any further efforts to improve the precision and consistency of these nuclear energy standards should be directed toward checking the absolute value for the Po^{214} alpha energy and the ratio of the $Li^7(p,n)Be^7$ threshold energy to the Po^{210} alpha particle energy. In any case the data at the present time appear to give overwhelming evidence that the Po^{210} alpha energy is some 0.1% higher than the older accepted value and is very close to 5.3045 Mev.

[9] Albrecht Rytz, Helv. Phys. Acta, **34–3**, 240 (1961).

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