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The Range-Energy Curves for Alpha-Particles and Protons

WILLIAM P. JESSE AND JOHN SADAUSKIS
Argonne National Laboratory, Chicago, Illinois
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Previous experiments have shown that in argon there exists a very good proportionality between the energy of an alpha-particle and the total ionization produced by it. In air this proportionality is not found, the ionization decreasing more rapidly than energy at low alpha-energies. Range-energy curves determined in the region 0–5 Mev, where the ionization in air is used as a measure of the alpha-energy, hence give too low energy values. Such curves, when corrected to equivalent ionization values in argon, show much better agreement with range and energy data derived from nuclear reactions. The range-energy curve for protons, derived from the alpha-curve, also shows improved agreement with nuclear data when the corrected alpha-range-energy curve is substituted for the old.

INTRODUCTION

IN a recent paper,[1] evidence has been presented for believing that in argon the ionization produced by a single alpha-particle is to a very good approximation proportional to the energy of the alpha-particle. From the work of Stetter[2] for alpha-particles in air, it was also shown that such a direct proportionality does not exist in air but that the relative ionization decreases markedly as the energy of the alpha-particle approaches zero.

As has already been pointed out in brief,[3] these findings have a very important bearing on the accuracy of the range-energy curves in current use for alpha-particles. Since, in the region from 0–5 Mev, there are no natural emitters of alpha-particles for which the absolute energies have been determined accurately, the range-energy curves in this region were of necessity constructed by estimating the energy of a slowed down alpha-particle by means of the ionization produced in some gas—almost universally air. Such curves are thus in reality range-ionization in air curves, and if the alpha-ionization in air is not proportional to the alpha-energy, they are subject to error, especially in the low energy regions. In the work of Holloway and Livingston,[4] the authors explicitly state that their curve is valid only if this direct proportionality in air exists. In the following paper, we have found means of converting the Holloway Livingston (henceforth denoted by H and L) ionization in air values to equivalent ionization in argon values, where, we believe, the above proportionality is almost exact. This results in a much more consistent agreement for the energy values from the range-energy curve with data from alpha-energies derived from nuclear transformations.

For clarity, the successive steps in the presentation below are indicated as follows:

I. Establishment of curve showing relative ionization in argon and in air for alpha-particles of different energies.
A. Experimental results from Sm-Po comparison in argon and in air.
B. Results of Gray-Gurney.
C. Further experimental measurements following method of Gurney.
II. Establishment of corrected range-energy curve for alpha-particles.
A. Correction of Holloway-Livingston curve from argon-air ionization ratios.
B. Attempt to establish absolute curve.
C. Comparison of original and corrected curves.
III. Comparison of energies derived from range-energy curves from known alpha-ranges with independently determined energies.
IV. Derived proton range-energy curve from alpha-particle curve.
V. Range-energy tables for protons and alpha-particles.

[1] Jesse, Forstat, and Sadauskis, Phys. Rev. **77**, 782 (1950).
[2] G. Stetter, Zeits. f. Physik **120**, 639 (1943).
[3] W. P. Jesse and J. Sadauskis, Phys. Rev. **75**, 1110 (1949); Phys. Rev. **76**, 163 (1949).
[4] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

TABLE I. Experimental values for different gases, relative to hydrogen, of W for alpha-particles of various ranges compared with that for a 20-mm range α-particle.

Residual range (mm of air)	2.5	5.0	7.5	10.0	15.0	20.0
Initial energy of α-particle (Mev)	0.33	0.9	1.4	1.9	2.7	3.4
Helium	1.00_1	1.00_2	0.98_8	1.00_6	0.99_7	(1.000)
Air, also N_2 and O_2	1.08_2	1.06_4	1.04_8	1.03_1	1.00_6	(1.000)
Neon	0.99_2	0.99_2	0.99_8	0.99_5	0.99_4	(1.000)
Argon	1.01_0	1.00_4	1.00_3	0.99_6	0.99_0	(1.000)

I. ESTABLISHMENT OF CURVE SHOWING RELATIVE IONIZATION IN ARGON AND IN AIR FOR ALPHA-PARTICLES OF DIFFERENT ENERGIES

A. Experimental Results from Sm-Po Comparison in Argon and in Air

A series of measurements has been made, both in argon and in air, to determine the ratio of the total ionization produced by an alpha-particle from samarium to that produced by a polonium alpha. As in our previous work, the ionization charge from a single alpha-particle was collected in an ion chamber and amplified by means of the vibrating-reed electrometer. The sudden jump recorded by the pen of the Brown recorder, into which the vibrating-reed feeds, is taken as a measure of the charge collected.

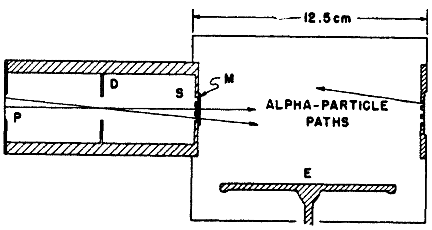

FIG. 1. Schematic diagram of collimating absorption cell and ionization chamber.

The ion chamber used for this comparison was cylindrical in shape with an internal diameter of 16 cm and height of 6 cm. The central electrode was a circular plate of stainless steel 14.5 cm in diameter. At its center and flush with the surface was a button of polished nickel on which the polonium sample was deposited. On both the faces of the electrode and on both stainless steel disks inserted in the ends of the chamber, samarium nitrate was sprayed in a thin layer from solution. The liquid spray was made up by diluting with water the solution obtained by treating a very pure sample of samarium oxide with nitric acid. Because of the large area covered, it was possible to get a counting rate in the chamber of three or four counts/min. and yet have the sample layer so thin as to give no serious self-absorption. The latter was judged by the calculated thickness of the layer from the amount of samarium nitrate sprayed on, and more accurately from the appearance of the plotted samarium alpha-peaks. These showed only a very small deviation from symmetry on the low energy side.

The ratio of alpha-ionization $(Sm/Po)_{argon}$ was determined from the mean of four runs to be 0.411, while $(Sm/Po)_{air}$ gave 0.390 as a mean for three runs. The ratio of these two values is 1.05_3. The "energies" for the Sm α, computed on the assumption of a direct proportionality between ionization and alpha-energy, are then 2.17_8 Mev and 2.06_9 Mev for argon and air, respectively, for an assumed energy for the polonium alpha of 5.298_4 Mev. The five percent discrepancy between these two values is much more than the error of experiment, estimated at not more than one percent. Thus, we have again the same evidence of departure in air from a linear relation between alpha-ionization and alpha-energy that was noted in our previous paper.

B. Results of Gray-Gurney

Such a dissimilarity between air and a group of gases comprising hydrogen and the noble gases has already been pointed out by L. H. Gray[5] on the basis of experimental measurements by Gurney.[6] These measurements were made on a collimated beam of alpha-particles partially stopped by passage through an air absorption cell in which the pressure of the air could be varied. For each approximately monoenergetic band of alpha-particles thus obtained, the ionization relative to that in hydrogen was measured for each gas. The anomalous behavior of air is shown in Table I, taken from the paper of Gray. Here in air the relative energy W to

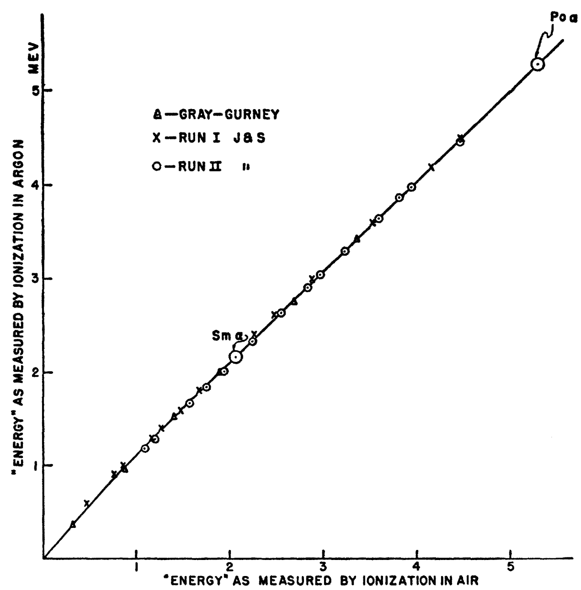

FIG. 2. "Energy" as measured by ionization in argon against "energy" as measured by ionization in air.

[5] L. H. Gray, Proc. Camb. Phil. Soc. **40**, 95 (1944).
[6] R. W. Gurney, Proc. Roy. Soc. A **107**, 332 (1925).

TABLE II. Ionization measurements relative to polonium in argon and in air.

"Energies" measured in air, Mev	5.30	4.00	3.5	3.0	2.5	2.0	1.5	1.00	0.50	0.30
"Energies" measured in argon	5.30	4.035	3.553	3.069	2.583	2.100	1.611	1.110	0.567	0.344
Ratio	1.00	1.009	1.015	1.023	1.033	1.050	1.074	1.110	1.134	1.147
Corresponding range from H and L curve	3.842	2.516	2.096	1.719	1.373	1.066	0.790	0.549	0.328	0.232
Energies from absolute argon measurements Mev	5.30	4.009	3.518	3.030	2.544	2.062	1.573			

make an ion pair increases with decreasing alpha-energy, in marked contrast to the behavior in the other gases.

C. Further Experimental Measurements Following Method of Gurney

We have made a series of measurements for the comparison of the relative ionization in argon and in air by essentially the same method as that used by Gurney, but covering a much larger range of alpha-energies. A collimating absorption cell (Fig. 1) allowed alpha-particles to pass through a perforated circular disk S into an ion chamber where they moved almost parallel to the surface of the collecting plate E. The ionization from each single alpha-particle was measured, both in argon and in air, by the method already described. The collimating chamber was an aluminum cylinder of 2.0-cm internal diameter and length 5.3 cm. The platinum plate P carrying the active polonium deposit was inserted at the base of the cylinder and was masked down by a plate with a circular aperture of 0.6 cm diameter. At the other end of the collimating cylinder the alpha particles passed into the ion chamber through the disk S pierced with a large number of small holes. These holes were 0.04 cm in diameter and covered a circular region 0.6 cm in diameter. This latter disk was covered with a gas-tight mica window M of about 0.6 mg/cm^2 equivalent thickness. A collimating aperture D half-way down the tube reduced the possibility of alpha-particles scattered from the walls emerging into the ion chamber.

The ionization for each group of alphas was measured, always relative to a standard polonium alpha-particle from a shallow collimating system C symmetrically placed with regard to the absorption cell, but diametrically opposite in the ion chamber. A small correction was always made here for the ions lost in the collimating holes.

The air admitted to the absorption cell was freed from moisture and carbon dioxide by passage through phosphorus pentoxide and potassium hydroxide tubes. From careful measurements of the temperature and pressure of the air in the cell, one could compute the relative air density, and hence the effective range absorbed by the air in the cell.

In Fig. 2, a curve is plotted from the above data. The ordinate for each point on the curve represents the ionization of a given alpha-particle relative to polonium in argon, and the abscissa represents the corresponding ionization value in air. For convenience, these values are expressed in "energies" calculated from a value for the polonium alpha of 5.298$_4$ Mev. The plot includes the samarium-polonium point, two runs with the

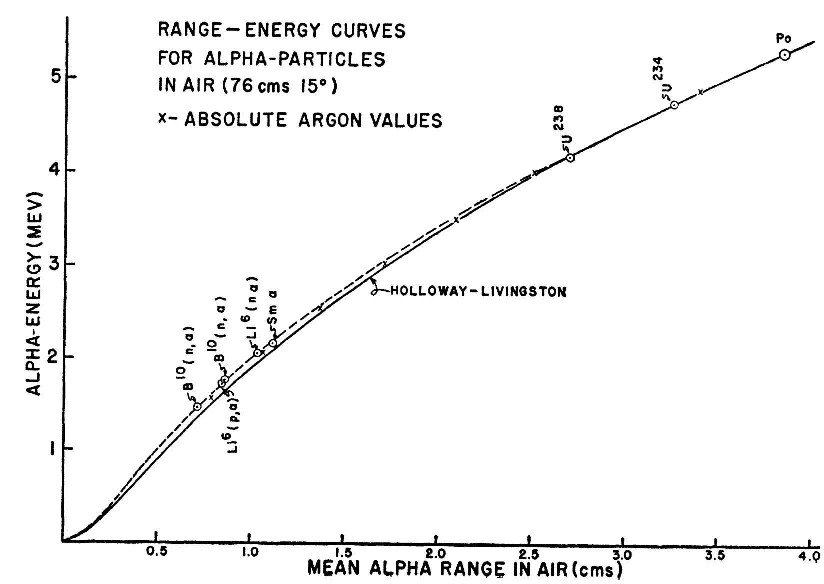

FIG. 3. A comparison of the H and L and H and L corrected range-energy curves.

TABLE III. Comparison of alpha-energies from range curves with independently determined energies.

Reaction	Range data: Source	Range cm	α-energies derived from ranges: H and L Mev	Corrected H and L Mev	Energies derived independently of ranges: α-energy Mev	Q-value	Source
$B^{10}(n,\alpha)$	Bower, Bretcher, and Gilbert[a] (corr.)	0.73_5					
	O'Ceallagh and Davis[b]	0.71_5					
	Bøggild[c]	0.70_9					
	Mean	0.72_0	1.35_5	1.46_8	1.47_4	2.31_6	Chao, Lauritsen, and Tollestrup[h]
$B^{10}(n,\alpha)$(ground)	Bøggild[c]	0.846					
	O'Ceallagh and Davis[b]	0.89_0					
	Mean	0.86_8	1.64_9	1.76_0	1.77_9	2.79_4	Chao, Lauritsen, and Tollestrup[h]
$Li^6(n,\alpha)$	Bøggild and Minnhagen[d]	1.04	1.95_4	2.06_1	2.06_0	4.78_8	Tollestrup, Fowler, and Lauritsen[i]
$Li^6(p,\alpha)$	Neuert[e]	0.85	1.61_3	1.72_4	1.72_6	4.01_7	Tollestrup, Fowler, and Lauritsen[i]
Sm α	Cuer and Lattes[f]	1.12	2.10	2.19	2.18		J and S
U^{238} α	Wytzes and Van der Maas[g]	2.70_2	4.19_6	4.20_0	4.18_0		Clark, Spencer-Palmer, and Woodward[j]
U^{234} α	Wytzes and Van der Maas[g]	3.25_8	4.76_0	4.76_0	4.76_3		Clark, Spencer-Palmer, and Woodward[j]

[a] Bower, Bretscher, and Gilbert, Proc. Camb. Phil. Soc. **34**, 290 (1938).
[b] C. O'Ceallagh and W. T. Davies, Proc. Roy. Soc. A **167**, 81 (1938).
[c] J. K. Bøggild, Kgl. Danske, Vid. Sels. Math-Fys. Medd. **23**, No. 4 (1945).
[d] J. K. Bøggild and L. Minnhagen, Phys. Rev. **75**, 782 (1949).
[e] H. Neuert, Physik Zeits. **36**, 629 (1935).
[f] P. Cuer and C. M. G. Lattes, Nature **158**, 197 (1946).
[g] S. A. Wytzes and G. J. Van der Maas, Physica **13**, 49 (1947).
[h] Chao, Lauritsen, and Tollestrup, Phys. Rev. **76**, 586 (1949).
[i] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).
[j] Clark, Spencer-Palmer, and Woodward, British Atomic Energy Projects Reports BR-521, 522 (1944).

absorption cell with two windows each of about 0.63 mg/cm^2, and points from the Gray-Gurney determinations. Since Gurney's data do not include alphas with residual range greater than 2.0 cm in air (air "energy" = 3.38 Mev) his highest point is fitted to the curve for this "energy."

II. ESTABLISHMENT OF CORRECTED RANGE-ENERGY CURVE FOR ALPHA-PARTICLES

A. Correction of Holloway-Livingston Curve from Argon-Air Ionization Ratios

As can be seen from Fig. 2 ,the agreement between the various determinations is very good. Values derived from the curve are shown more accurately in Table II. In the first horizontal row are shown "energy" values relative to polonium from ionization measurements in air. These "energy" values correspond to those on the H and L curve. In the second row are given the corresponding "energies" from ionization in argon which are read from Fig. 2. The third row gives the ratios of these two sets of measurements. For the sake of completeness the corresponding alpha-ranges from the H and L curve are given in the fourth horizontal row. It is at once apparent that the energy values determined in argon are in places more than 100 kev higher than the original ones determined in air. This discrepancy is particularly marked in the region of low alpha-energies, just the region where the H and L curve has been known to give too low energy values for various nuclear reactions. A complete plot of the H and L curve and the corrected curve are shown in Fig. 3.

It should be pointed out that so far no evidence has been presented to prove or disprove the essential correctness of the H and L curve in representing the ionization in air as a function of alpha-particle range. In our own experiments the absorption cell was used as a somewhat imperfect monochromator for alpha-particles, and the *ratio* of ionization for argon and air can be measured without any precise knowledge of the residual ranges. In fact, the only thing which needs to be assumed is the constancy of conditions within the monochromator during the period of the comparison. Hence the absolute accuracy of the derived argon curve in giving true energies can be no better than the absolute accuracy with which the H and L curve represents the corresponding relation for conditions in air.

B. Attempt to Establish Absolute Curve

An attempt has been made to determine an absolute range-ionization in argon curve for comparison with the above derived curve. This involves an accurate estimate of the residual range for each alpha-particle used and hence of the portion of the range absorbed in each case by the air cell and the mica window. Since the stopping power of mica is a function of the energy of the alpha-particle, any exact determination of the window correction becomes difficult.

An estimate of this variable correction was made experimentally by an auxiliary run supplementing our second run. An additional window, cut from the same small piece of mica, was put just before the original window, and a series of measurements in argon was again made with varying air pressures in the absorption cell. From the single and double window plots of ionization in argon, relative to polonium, against effective range absorbed by the air in the absorption cell, it was possible to determine extrapolated ionization values for a windowless cell.

One further small correction was made because of the fact that in the absorption cell with a slightly divergent beam of alpha-particles, the average path was greater than the geometrical length of the cell, 5.344 cm. This resulted in increasing this effective length by 0.35 percent. The range absorbed in the air of the cell was then calculated, subtracted from the mean range of the polonium alpha, 3.842 cm, to obtain the residual range in argon. From a plot of the extrapolated ionization in argon against such ranges the "energy" values shown in the last horizontal row of Table II were obtained, corresponding to the range values in row 4. These values are also shown as small crosses in Fig. 3.

The agreement between such values and those derived from the H and L curve in row 2 is only fair, the directly measured energy values being some 30 to 40 kev lower for the alpha-particles of lower energy. Such an energy difference would correspond to an underestimate of the absorbed range values for the direct measurement by about 0.015 cm. Considering the uncertainty of the window corrections, such an underestimate seems quite possible. Perhaps the principal value of the direct measurements is to exemplify the difficulties in determining range-energy curves by what seems at first glance the ideal method; i.e., direct range determinations in air from particles artificially accelerated in a high voltage apparatus.

C. Comparison of Original and Corrected Curves

In Fig. 3 is shown the original H and L curve as a full line and as a dashed line the corrected curve obtained from the H and L curve and the values given in Fig. 2 and Table II. For each H and L energy value, derived from ionization in air, is substituted the corresponding "energy" as measured from ionization in argon taken from Fig. 2. The absolute measurements in argon from Table II are shown as small crosses but no use was made of these values in drawing the corrected curve. It is believed, largely because of the uncertainties connected with the window correction, that these data are inherently less accurate than those derived from the apparently carefully constructed H and L curve and our argon-air ionization ratios.

It should be noted that Holloway and Livingston in the construction of their original curve used their ionization in air values only up to a range of 2.8 cm (4.3 Mev) and joined the lower curve to a curve extra-

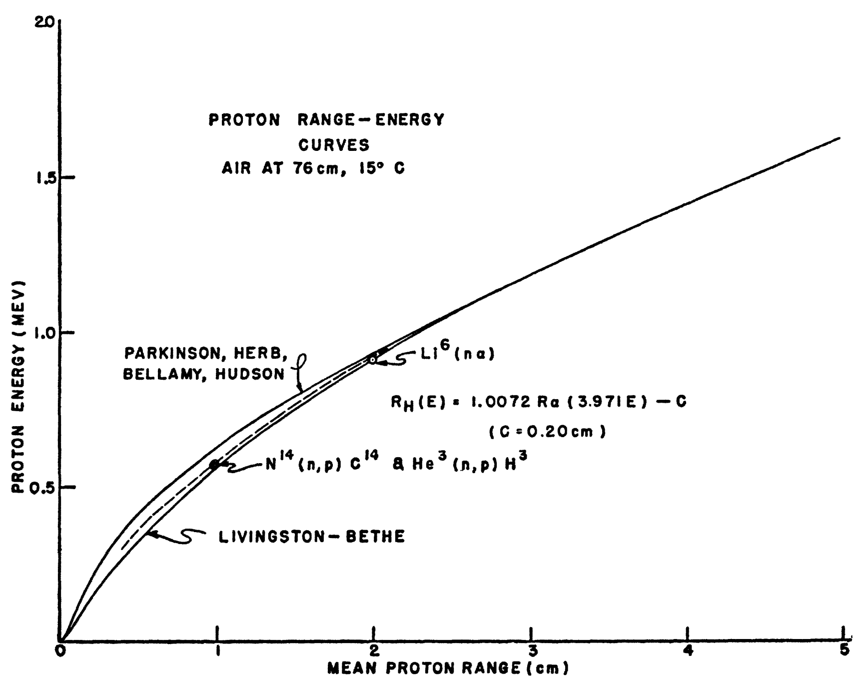

FIG. 4. A comparison of range-energy curves for protons.

TABLE IV. Comparison of proton energies from range curves with independently determined energies.

Reaction	Range Cm	Range Source	Derived energy from curves—Mev: Parkinson, Herb, Bellamy and Hudson	Livingston and Bethe	Corrected Livingston and Bethe	Independently determined energies Mev
$N^{14}(n,p)C^{14}$	0.991	Hughes and Eggler[a]	0.623	0.557	0.575	0.581
$N^{14}(n,p)C^{14}$	1.00	Cornog, Franzen, and Stephens[b]	0.627	0.561	0.579	0.581
$He^{3}(n,p)H^{3}$	0.980	Hughes and Eggler[a]	0.620	0.552	0.572	0.569
$Li^{6}(n,\alpha)H^{3}$	2.00	Bøggild and Minnhagen[c]	0.933	0.910	0.919	0.911[d]

[a] D. J. Hughes and C. Eggler, Phys. Rev. 73, 809 (1948).
[b] Cornog, Franzen, and Stephens, Phys. Rev. 74, 1 (1948).
[c] See footnote d of Table III.
[d] See footnote i of Table III.

polated from the accurately known range and energy values for alpha-particles of 5.3 Mev and above. Hence in the region from 4 to 5 Mev their curve is no longer a pure range-ionization in air curve, and it is a matter of judgment as to how large a correction should be here applied. Somewhat arbitrarily, therefore, no further corrections were applied above about 2.8-cm range and the corrected curve was made to merge into the original H and L curve smoothly at about this point. Had the full corrections been applied, this would have resulted in a raising of energy values in the region by about 20 kev. The drawing of the curve in this way is, in part, justified by the slightly better agreement obtained with the directly determined range and energy values for the alpha-particle from U^{234}, as shown below.

III. COMPARISON OF ENERGIES DERIVED FROM RANGE-ENERGY CURVES FROM KNOWN ALPHA-RANGES WITH INDEPENDENTLY DETERMINED ENERGIES

In Table III is shown a compilation of energy values derived from the H and L and H and L corrected curves from the use of alpha-particle ranges given in the literature. These derived energy values are compared with directly determined energies found elsewhere in the literature. It should perhaps be emphasized that the agreement here is, in most cases, an absolute one, since the corrected curve was not constructed to pass through any calibration points, but solely by the use of the H and L curve with our own corrections relating argon and air.

Where ranges are measured in some other gas than air, as is often the case in cloud-chamber work, a rather complicated correction must often be made in reducing the measured ranges to equivalent ranges in air, because of the variation in stopping power with energy of the gases used. Such a correction has been calculated for the alpha-range for the $B^{10}(n,\alpha)Li^{7*}$ reaction from the work of Bower, Bretcher, and Gilbert (reference a, Table III). The value has been raised from an uncorrected range of 0.70 cm to 0.735 cm.* This is not as large a correction as Gilbert[7] himself has recently suggested. For the other two values for $B^{10}(n,\alpha)$ and in the work of Bøggild and Minnhagen such corrections have apparently been made by the authors. In the older determination of Neuert for the range of the alpha-particle from the reactions $Li^{6}(n,\alpha)H^{3}$, carried out in a cloud chamber filled with hydrogen, apparently no correction of this sort was made. Hence this range value must be regarded as more uncertain. Account was, however, taken of the variation in stopping power with energy in a photographic emulsion by Cuer and Lattes[8] in the determination of the range in air of the alpha-particle from samarium. Their value is also in agreement with the older direct determination in air of 1.13 cm by Hosemann.[9]

It will be seen in vertical column 4, Table III, that the H and L curve gives, in general, much lower energy values than those derived from direct measurements (vertical column 6) made largely by the magnetic deflection of alpha-particles by the group† at the California Institute of Technology. On the other hand, the energy values derived from the ranges from the corrected H and L curve show an agreement with the absolute values far better than one has a right to expect. From the limited accuracy of the data, particularly the range measurements, an agreement within one percent would be very satisfactory. The almost exact agreement in several places is undoubtedly due purely to chance.

It should be noted that in the absence of absolute energy measurements for the alpha-particles from Sm, U^{238}, and U^{234}, energy values derived from relative ionization measurements in argon have been used. The direct comparison in argon for Sm with Po by Jesse and Sadauskis, already mentioned, has been used to obtain the energy value 2.18 Mev. Likewise, the values for U^{234} and U^{238} are taken from argon ionization comparisons. Clark, Spencer-Palmer, and Woodward[10] have found values of 4.763 and 4.180 Mev for these two

* We are indebted to Professor H. A. Bethe for a private communication giving this corrected value.

[7] C. W. Gilbert, Proc. Camb. Phil. Soc. 44, 447 (1948).
[8] See reference f of Table III.
[9] R. Hosemann, Zeits. f. Physik 99, 405 (1936).
† We are indebted to Professor W. A. Fowler for a private communication giving us these values before their formal publication.
[10] See reference j of Table III.

alpha-particles. It should be pointed out that the correctness of these energy values depends upon the assumption as to a direct proportionality between ionization in argon and energy, which is just the same assumption upon which rests the correctness of the energy values given by the corrected range-energy curve. Hence any agreement between the values in columns 5 and 6 does not, for the last three values, indicate in itself that these are necessarily the true energy values corresponding to the given ranges. The agreement does indicate, however, the consistency of the various argon ionization measurements.

IV. DERIVED PROTON RANGE-ENERGY CURVE

In the region above 0.3 Mev, Livingston and Bethe[11] have derived a range energy relation for the proton from that of the alpha-particle by the use of the equation $R_H(E)=1.0072R\alpha(3.971E)-C$. This equation is simply an expression of the fact that two particles of unequal masses lose energy at the same rate for equal velocities, and that the rate of loss of energy is proportional to the square of the particle charge. $R\alpha$ and R_H denote, respectively, the corresponding alpha- and proton ranges and $C=0.20$ cm is an empirical constant introduced from the cloud-chamber measurements of Blackett to account for the difference in behavior of protons and alpha-particles at low energies. Here, because of the capture and loss of electrons, the charge ratio between the alpha-particle and proton does not remain precisely two to one.

Since the proton range-energy curve was based on the corresponding alpha-curve, any change in the latter obviously necessitates a change in the former. Accordingly, the proton curve has been recalculated with the values for the corrected H and L curve substituted for the older values. As shown in Fig. 4, the corrected curve in the region of 0.5 Mev is about 20 kev higher than the former Livingston and Bethe curve, but is still lower than the experimental curve of Parkinson, Herb, Bellamy, and Hudson.[12]

The relation between these curves is best shown in Table IV where the derived energies from known range values are compared with directly determined energies. In the first three horizontal rows, proton ranges from cloud-chamber determinations for the (n,p) reactions for N^{14} and He^3 are used to determine the energies from each of the three range-energy curves. These derived energies are to be compared with the corresponding energies calculated from the $(n-H^1)$ mass difference. In these calculations $(n-H^1)$ was somewhat arbitrarily chosen[13, 14] as 0.778 Mev and the C^{14} and H^3 β-end points were taken to be 155 and 19 kev, respectively.

[11] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).
[12] Parkinson, Herb, Bellamy, and Hudson, Phys. Rev. **52**, 75 (1937).
[13] Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).
[14] Taschek, Jarvis, Argo, and Hemmendinger, Phys. Rev. **75**, 1268 (1949).

TABLE V. Alpha-energy values for tabulated mean ranges in air 15° and 760 mm.

Mean ranges cm	Alpha-energies Mev	Inter-polation differences	Mean ranges cm	Alpha-energies Mev	Inter-polation differences
0.20	0.271	0.111	2.2	3.668	0.117
0.25	0.382	0.126	2.3	3.785	0.111
0.30	0.508	0.127	2.4	3.896	0.107
0.35	0.635	0.126	2.5	4.003	0.100
0.40	0.761	0.121	2.6	4.103	0.097
0.45	0.882	0.112	2.7	4.200	0.100
0.50	0.994	0.111	2.8	4.300	0.100
0.55	1.105	0.109	2.9	4.400	0.102
0.60	1.214	0.106	3.0	4.502	0.100
0.65	1.320	0.102	3.1	4.602	0.100
0.70	1.422	0.103	3.2	4.702	0.096
0.75	1.525	0.099	3.3	4.798	0.093
0.80	1.624	0.099	3.4	4.891	0.096
0.85	1.723	0.093	3.5	4.987	0.092
0.90	1.816	0.092	3.6	5.079	0.090
0.95	1.908	0.087	3.7	5.169	0.091
1.00	1.995	0.167	3.8	5.260	0.090
1.10	2.162	0.159	3.9	5.350	0.090
1.20	2.321	0.149	4.0	5.440	0.087
1.30	2.470	0.153	4.1	5.527	0.087
1.40	2.620	0.147	4.2	5.614	0.084
1.50	2.767	0.140	4.3	5.698	0.085
1.60	2.907	0.137	4.4	5.783	0.086
1.70	3.044	0.130	4.5	5.870	0.083
1.80	3.174	0.132	4.6	5.953	0.082
1.90	3.306	0.129	4.7	6.035	0.085
2.00	3.425	0.124	4.8	6.120	0.082
2.10	3.549	0.119	4.9	6.202	0.081
			5.0	6.281	

The energy values computed on the basis of the value of $(n-H^1)$ chosen agree very well with the values derived from ranges for the corrected Livingston and Bethe curve, but the energy values from their original curve are almost 20 kev too low. The Parkinson, Herb, Bellamy, and Hudson curve give definitely higher values.

In the last row of the table is given the comparison from the cloud-chamber determination of Bøggild and Minnhagen for the range 6.00 cm of the tritium particle in the reaction $Li^6(n,\alpha)H^3$. The equivalent range for a corresponding proton is 2.00 cm. The corresponding energy as calculated from the work of Tollestrup, Fowler, and Lauritsen (see footnote i of Table III) for a Q-value of 4.788 Mev is 0.911 Mev. Since the corrected and uncorrected Livingston and Bethe curves converge at about this point, the curves give very nearly the same energy value, both showing good agreement with the absolute determination.

The relation used to derive the proton curve is obviously inexact at low energies, since for energies near zero it would give a negative proton range. The equation, therefore, has not been used for proton energies less than 0.3 Mev. A plausible curve can, of course, be extrapolated to the origin, falling slightly higher than the original Livingston-Bethe curve, but such a procedure can hardly give very exact values. Hence no values have been computed for energies lower than 0.3 Mev.

TABLE VI. Proton energies as a function of mean proton range in air at 15° and 760 mm.

Mean proton ranges cm	Proton energies Mev	Inter-polation differences	Mean proton ranges cm	Proton energies Mev	Inter-polation differences
0.4	0.302	0.055	2.7	1.103	0.025
0.5	0.357	0.049	2.8	1.128	0.026
0.6	0.406	0.047	2.9	1.154	0.025
0.7	0.453	0.046	3.0	1.179	0.023
0.8	0.499	0.042	3.1	1.202	0.024
0.9	0.541	0.040	3.2	1.226	0.024
1.0	0.581	0.038	3.3	1.250	0.024
1.1	0.619	0.037	3.4	1.274	0.022
1.2	0.656	0.036	3.5	1.296	0.022
1.3	0.692	0.036	3.6	1.318	0.022
1.4	0.728	0.036	3.7	1.340	0.022
1.5	0.764	0.032	3.8	1.362	0.022
1.6	0.796	0.031	3.9	1.384	0.022
1.7	0.827	0.032	4.0	1.406	0.022
1.8	0.859	0.030	4.1	1.428	0.022
1.9	0.889	0.030	4.2	1.450	0.021
2.0	0.919	0.029	4.3	1.471	0.021
2.1	0.948	0.029	4.4	1.492	0.021
2.2	0.977	0.025	4.5	1.513	0.021
2.3	1.002	0.025	4.6	1.534	0.020
2.4	1.027	0.024	4.7	1.554	0.020
2.5	1.051	0.026	4.8	1.574	0.020
2.6	1.077	0.026	4.9	1.594	0.020
			5.0	1.614	

V. RANGE-ENERGY TABLES FOR PROTONS AND ALPHA-PARTICLES

For useful reference the results for these alpha- and proton range-energy relations are shown in Tables V and VI. Here the corresponding energies are given for mean ranges increasing in equal steps. All range values are given for air at 15°C and 760-mm pressure. For convenience, interpolation values are tabulated showing the energy change for the range interval indicated, that is, the average slope of the range-energy curve at this point. Parenthetically, it may be noted that the use of such slopes on the range-energy curve provides probably the most accurate method of determining energies from range data, provided one has a standard particle of known energy for comparison. Thus, if one measures experimentally the small difference between the ranges of an unknown and known alpha-particle, then the energy differencc between the two alphas may be computed from the slope of the range-energy curve in this region and the final result may be fairly accurate, even though the range-energy curve may give incorrect absolute energy values.

It is believed that the energy values for alpha-particles in Table V are accurate to within about 30 kev below 1 Mev and to 20 kev thereafter. The estimation of error in the proton values is more difficult, since the only calibration points in the low energy region depend on the value of $(n-H^1)$ for which there is still some degree of uncertainty. The comparatively large empirical constant $C=0.2$ cm in the transformation equation also offers an additional uncertainty. Unless, however, the true value of $(n-H^1)$ should prove eventually to be quite different from the value 778 kev assumed, it is believed that the energy values given are accurate to within 20 kev. Similar range-energy curves have recently been constructed by H. A. Bethe and are to be found in a publication of the Brookhaven National Laboratory. These are in good agreement with the present work. This is rather to be expected since the data used and the methods of construction are almost the same.

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