Alpha-Particle Ionization in Polyatomic Gases and the Energy Dependence of W*†

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An extended series of measurements by three different methods has been carried out to determine the variation of W, the average energy to make an ion pair in the gases N_2 and C_2H_4 as a function of the energy of the ionizing alpha particle. In one method, the ionization ratios were determined in the two gases for single alpha particles from two collimated polonium sources, the particles from one source being reduced in energy by passage through a succession of interchangable mica windows. The corresponding energy ratios were determined by auxiliary measurements in pure argon, the W values in argon being assumed constant. W values for alphas of initial energy up to 9 Mev were also obtained by a comparison in C_2H_4 and N_2 of the relative ionization from Po and ThC′ single alpha particles. Data from all these experiments indicate a continuous decrease in W values in C_2H_4 and N_2 with increasing alpha energy over a range from 1–9 Mev. The differential w (defined as the ratio of energy increment ΔE to ionization increment ΔI at any point on the alpha path) also decreases similarly and seems to approach but never quite reach, within the limits of alpha energy so far investigated, the corresponding W value for beta particles. No explanation of this continuous decrease with energy of the W values can at present be advanced.

INTRODUCTION

AMONG the more interesting problems connected with the ionization by alpha particles in gases is a determination of the variation of W, the average energy to produce an ion pair in a gas as a function of the energy of the ionizing alpha particle. As a result of a comparison of the relative ionization by single alpha particles of various energies in very pure argon, it has been found[1] that no variation in the value of W greater than the experimental error of 0.4% could be detected for alpha particles ranging in energy from 1 to 9 Mev. In all these experiments a method of total ionization was employed, involving a collection of both positive and negative ions within the chamber.

From relative comparison measurements in different gases by Gurney,[2] it has been shown by Gray[3] that this apparent invariance in W with alpha energy probably exists in all the noble gases and in hydrogen, within the limit of accuracy of Gurney's results—about 1%. Such a result has also been confirmed by additional relative measurements of our own.[4]

For gases other than the noble gases and hydrogen, a large number of experiments over the last fifty years might be cited. These experiments indicate that, in this general class of gases, the value of W is not constant but increases with decreasing alpha-particle energy. This is also in accord with the findings of Gray and Gurney.

Unfortunately, a large number of these experiments were carried out in air at atmospheric pressure, where the process of columnar recombination plays a disturbing role. Since such recombination varies as the square of the ionic density, the collection of ions with fields of magnitude commonly used is less complete in the very dense tracks for particles of low energy than in the more attenuated tracks at higher energies. Such an effect would in itself tend to produce an increase in the measured W values with decreasing energy.

In addition to this problem of the collection of ions, there are many other difficulties which make the determination of the variation of W with alpha energy a problem requiring the greatest care and the highest precision of measurement. Such research has been attempted by the present author by various methods at intervals during the past six years, and the present paper is a compilation of the results collected during this time.

METHODS AND APPARATUS

During the period mentioned this problem has been attacked by three variants of the fundamental method.

(a) In the last and most extensive series of measurements use has been made of the long ionization chamber [Fig. 1(a)], described in some detail in a previous paper.[5] Here two collimated polonium alpha sources

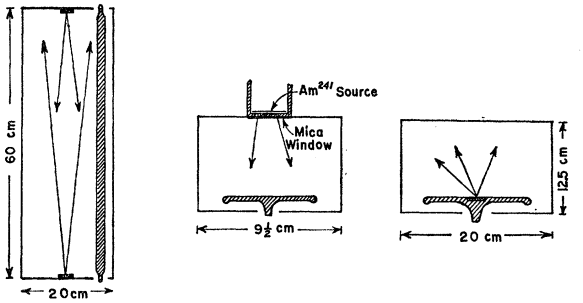

FIG. 1. Schematic diagram for ionization chamber employed in each of three experimental methods used.

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† A summary of the preliminary work in this paper was presented at an informal conference at Gatlinburg in September, 1958, sponsored by the National Research Council. For published report, see reference 11.

[1] W. P. Jesse, H. Forstat, and J. Sadauskis, Phys. Rev. **77**, 782 (1950).

[2] R. W. Gurney, Proc. Roy. Soc. (London) **A107**, 332 (1925).

[3] L. H. Gray, Proc. Cambridge Phil. Soc. **40**, 95 (1944).

[4] W. P. Jesse and J. Sadauskis, Phys. Rev. **97**, 1668 (1955).

[5] W. P. Jesse, Radiation Research **13**, 1 (1960).

TABLE I. Direct measurements for determination of reduced alpha ionization in Ar, C_2H_4, and N_2.

Number of window arrangement	Combined window density (mg/cm²)	Ratio red. α/Poα argon	Calculated energy red. α (Mev)	Ratio red. α/Poα C_2H_4	No. ion pairs for red. α C_2H_4	W for C_2H_4 (ev/ion pair)	Ratio red. α/Poα N_2	No. ion pairs for red. α N_2	W for N_2 (ev/ion pair)
0	0		5.291		188 760	28.03		145 400	36.39
(1)	1.073	0.8697	4.602	0.8610	162 520	28.32	0.8642	125 650	36.63
		0.8687	4.597	0.8634	162 980	28.20	0.8633	125 520	36.62
						28.26			36.63
(2)	2.134	0.7201	3.810	0.7093	133 880	28.46	0.7114	103 440	36.84
		0.7204	3.812	0.7077	133 590	28.53	0.7120	103 520	36.82
						28.50			36.83
(3)	3.207	0.5451	2.884	0.5312	100 270	28.77	0.5334	77 550	37.19
		0.5457	2.888	0.5313	100 270	28.80	0.5340	77 630	37.19
						28.79			37.19
(4)	4.436	0.2952	1.562	0.2839	53 580	29.15	0.2843	41 330	37.80
		0.2942	1.557	0.2837	53 550	29.07	0.2834	41 210	37.78
						29.11			37.79
(5)	4.853	0.1944	1.029	0.1840	34 730	29.62	0.1851	26 910	38.23
		0.1949	1.031	0.1838	34 700	29.72	0.1849	26 890	38.35
						29.67			38.29

were attached to the two end plates of the chamber. The lower collimator was open; the face of the upper could be covered by a succession of mica windows of varying thickness. The upper collimator was mounted on a removable plug, so that the window arrangement could be changed without disturbing the internal geometry of the chamber.

By means of the system[5] employed heretofore of the vibrating reed electrometer feeding into a Brown strip-chart recorder, the ratio of the mean ionization jump for the reduced alpha to that for the polonium alpha was obtained. Such ratios were determined with each window arrangement for each of the gases Ar, C_2H_4, and N_2. To obtain a convenient measure of the reproducibility of such ratios, two series of runs were made for each window for each gas, where each series consisted of two and sometimes three runs. Each run involved the comparison of several hundred alpha jumps. The ratios determined for these two series have been recorded for the three gases in columns 3, 5, and 8 of Table I and constitute the raw data from which all further computations have been made. Although there is no notation to that effect in the table, the first figure for each window is the ratio for series I, the second the ratio for series II. The agreement between the two series is seen to be very good, the deviation from the mean being of the order 0.1%—0.2%. Throughout all the calculations, each series has been treated as an independent experiment in itself. Thus, from a comparison of the two series one has a rough measure of the reproducibility of the results, even in those cases where the process of calculation enormously increases the percent errors involved.

It should be pointed out that the employment of such experimental ratios enables one to use the present apparatus at its highest precision, since such a method minimizes the effect of minute drifts in the sensitivity of the system, possible small changes of capacitance, and possible small alterations in the composition of the chamber gas due to evolution of gases within the system. For the measurements in argon, which is particularly sensitive to minute traces of those hydrocarbon gases which may discharge metastable states, all measurements were carried out with the gas continuously circulating through the chamber from a purification system of a cocoanut charcoal tube immersed in a mixture of solid CO_2 and acetone.

The difficulties due to incomplete collection of ions because of columnar recombination, which are so troublesome in ionization experiments in air, were avoided to a large extent by the use of the three gases Ar, N_2, and C_2H_4. Since these gases do not form molecular negative ions, the effects of recombination are much less marked than in air. Even in air, however, it has recently been shown[5] that for the pressures of the order of 5 cm of mercury used in the long chamber, the effect of columnar recombination upon the measurements is negligible.

(b) In addition to the measurements just described, earlier measurements by a similar but cruder method have been included in this paper. In this second method, alpha particles from an Am^{241} source,[4] deposited on a platinum disk, were collimated and allowed to pass from an evacuated region through a mica window into an ionization chamber [Fig. 1(b)]. Additional sheets of mica could be inserted above the window to vary by

steps the energy of the reduced alpha particle. For each window arrangement, the relative ionization current was measured by a drift method in CH_4 and N_2 at pressures of the order of 45–50 cm of mercury and compared with the current under similar conditions in pure argon, continuously circulating through the chamber from the purification system. On the assumption that the W for pure argon is invariant with energy at a value of 26.4 ev/ion pair, the W values in N_2 and CH_4 could be determined from the corresponding current ratios for each reduced alpha energy.

The W values obtained thus have been plotted as points △ in Fig. 2 for comparison with the more precise results of method (a). The corresponding energies, plotted as abscissas, have been estimated from alpha range measurements made within the chamber. Since such energy values are used only for the purposes of the plot, no extraordinary precision is necessary here.

(c) Older results from a third experimental method have also been included as points denoted by + on the curves in Fig. 2. The measurements carried out consisted of two comparisons of the relative ionization in N_2 and C_2H_4 by uncollimated alpha particles from U^{238} and Po^{210} and also from ThC′ and Po^{210}. Such comparisons were made in a cylindrical chamber 20 cm in diam [Fig. 1(c)] and 12.5 cm high at gas pressures of approximately one atmosphere. The alpha particles all had their origin in very weak radioactive sources laid down upon a stainless-steel button, inserted at the center of the circular disk electrode. The uranium deposit was formed from a nitrate solution of depleted U^{238}.

The ratios of the mean ionization jumps for the Poα and the ThC′ alpha were determined by the procedure of method[5] (a). From a knowledge of the W values for the Poα in N_2 and C_2H_4 the corresponding values for ThC′ and U^{238} could be readily calculated (Table III). Since the energies for all these alpha particles are known with high precision, there is no need here for estimations of energy through auxiliary measurements in argon.

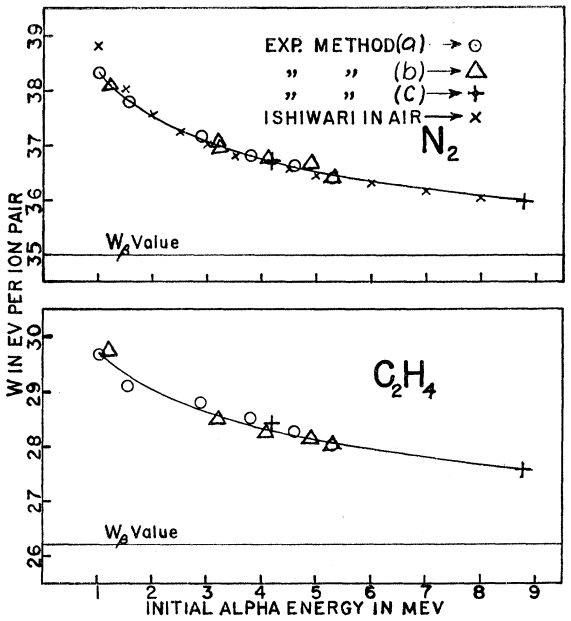

FIG. 2. W values obtained in N_2 and C_2H_4 plotted against the initial energy of the ionizing alpha particles employed.

RESULTS

Detailed calculations from the results of method (a) are given in Tables I and II. In columns 3, 5, and 8 of Table I are recorded the ionization ratios of the reduced alpha to the polonium alpha for each of the window arrangements. As was noted before, in Table I the top value for each window denotes the ratio for series I, the lower result for series II. In column 4 the energies are computed for the reduced alphas from the ratios in argon in column 3. This is on the tacit assumption of the invariance of W in argon with alpha energy. The energy for the comparison polonium alpha issuing from the open collimator was assumed to be 5.291 Mev, a result obtained by correcting the value[6] 5.3007 Mev by

TABLE II. Calculated values for intervals from difference combinations of data in Table I.

Window combination difference	Initial α energy (Mev)	Final α energy (Mev)	Energy interval (Mev)	ΔI No. of ion pairs for interval in C_2H_4	w for C_2H_4 (ev/ion pair)	ΔI No. of ion pairs or interval in N_2	w for N_2 (ev/ion pair)
(0–1)	5.3007	4.599	0.702	26 360	26.6_3	20 080	34.9_6
(1–2)	4.599	3.811	0.788	29 010	27.1_6	22 110	35.6_4
(0–2)	5.3007	3.811	1.490	55 370	26.9_1	42 180	35.3_2
(2–3)	3.811	2.886	0.925	33 470	27.6_4	25 890	35.7_3
(0–3)	5.3007	2.886	2.415	88 840	27.1_8	68 070	35.4_8
(1–3)	4.599	2.886	1.713	62 480	27.4_2	47 990	35.6_9
(3–4)	2.886	1.559	1.327	46 700	28.4_2	36 320	36.5_4
(2–4)	3.811	1.559	2.252	80 170	28.1_0	62 210	36.2_0
(1–4)	4.599	1.559	3.040	109 180	27.8_4	84 320	36.0_5
(4–5)	1.559	1.030	0.530	18 850	28.1_2	14 370	36.8_8
(3–5)	2.886	1.030	1.856	65 550	28.3_1	50 700	36.6_1
(2–5)	3.811	1.030	2.781	99 020	28.0_9	76 580	36.3_1

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

TABLE III. Ionization comparison of Po^{210} with U^{238} and ThC′, [method (c)].

Gas	Ion ratio U^{238}/Po	Ion pairs for Po	Ion pairs for U^{238}	W for U^{238}	w for interval 5.3007–4.195 Mev	Ion ratio ThC′/Po	Ion pairs for ThC′	W for ThC′	w for interval 8.7801–5.3007 Mev
N_2	0.7840	145 660	114 200	36.7_3	35.1_4	1.676	244 130	35.9_7	35.3_4
C_2H_4	0.7806	189 110	147 620	28.4_2	26.6_5	1.681	317 890	27.6_1	27.0

the estimated energy loss within the collimator holes. This loss was evaluated by the same procedure used in former experiments in air.[5] Again, the true loss was assumed to be 0.4 the calculated loss within the collimator holes.

Similarly from the ratios in columns 5 and 8, the total number of ions produced by the various reduced alphas in N_2 and C_2H_4 was computed by a multiplication of these ratios by the number of ions produced by the collimated Poα (see top line of Table I). These values for the number of ions produced were taken from absolute precision measurements in C_2H_4 and N_2 described in the paper already mentioned,[5] and such values have been similarly adjusted to account for the loss of ions within the collimator holes, The former precision measurements give 36.39 and 28.03 ev/ion pair for W in N_2 and C_2H_4, respectively, for Poα.

The need for collimator corrections for the reduced alphas was avoided by adjustment of the pressures in the measurements in the three gases, all of the order of 5 cm of mercury, in the inverse ratio of their stopping powers relative to air. Thus, in each gas the reduced alpha was retarded by the mica window plus an equivalent gas path within the collimator holes. The stopping powers relative to air were taken as 0.929, 0.99, and 1.31 in Ar, N_2, and C_2H_4, respectively.

The W values for C_2H_4 and N_2, obtained by dividing the energy values of column 4 by the number of ions derived in columns 6 and 9, are shown in columns 7 and 10 of Table I. The agreement between the values for the two series is excellent. Similar agreement may be obtained by the statistical variant of pairing the energy values from series I with the ion pair values of series II and vice versa.

It should be noted that the W values here obtained refer to the average energy to make an ion pair for a reduced alpha of initial energy given in column 4, which expends all its energy within the gas. This mean W is seen to increase continuously as the initial energy of the alpha particle decreases.

These W values have been plotted as ordinates in Fig. 2 with the corresponding initial alpha energies as abscissas. For comparison, W_β values of 35.0 ev/ion pair in N_2,[7] and 26.2 ev/ion pair in C_2H_4, derived for beta particles, have been indicated as horizontal lines in the figures.

[7] W. P. Jesse and J. Sadauskis, Phys. Rev. **109**, 2002 (1958).

Additional experimental points denoted by △ have been added in Fig. 2. These come from the cruder current comparisons designated above as method (b). In the plot for N_2 the directly measured values from method (b) have been used. In the latter method, however, no measurements were made in C_2H_4, but similar measurements were carried out in CH_4. Hence, in order to compare the shape of the two curves, that for CH_4 was arbitrarily made to coincide with the curve for C_2H_4 at the energy corresponding to the polonium alpha. That is, all the ordinates of the CH_4 curve were reduced in the ratio 28.0/29.2, the ratio of the respective W's in C_2H_4 and CH_4 for the polonium alpha particle. It will be seen that the points thus calculated, as well as the directly determined values for N_2, fall very well on the curves in Fig. 2.

Computations of W for U^{238} and ThC′ from the measurements of method (c) are shown in Table III. Ionization ratios relative to polonium are indicated in columns 2 and 7. The number of ion pairs generated by the polonium alpha in the two gases from the absolute precision measurements[5] already mentioned are given in column 3. The number of ion pairs for U^{238} and ThC′ are thus easily calculated and appear in columns 4 and 8. The W values in columns 5 and 9 are then computed on the basis of the accurately known energies of 4.195[8] and 8.7801[6] Mev for U^{238} and ThC′, respectively. These are plotted as + in Fig. 2.

Finally, additional points have been added to Fig. 2, based upon the measurements of Ishiwari *et al.*,[9] made in air at atmospheric pressure where saturation was obtained by the use of fields as high as 11 400 v/cm. The results of this experiment as to the number of ions collected in air as a function of alpha energy have already been shown to be in satisfactory agreement with similar recent results of our own in air (see Fig. 5 in reference 5).

In the work of Ishiwari, an empirical formula is given, $W=0.948+0.119/\sqrt{E}$, relating experimental W values in air to the initial alpha energy E. For comparison with results in Fig. 2 for N_2, this W value is arbitrarily taken to be 36.39 ev/ion pair for the Po alpha energy. From ratios derived from the formula, the variation of W on this basis can be determined. The calculated values

[8] B. G. Harvey, H. G. Jackson, T. A. Eastwood, and G. C. Hanna, Can. J. Phys. **35**, 258 (1957).

[9] R. Ishiwari, S. Yamashita, K. Yuasa, and K. Miyake, J. Phys. Soc. Japan **11**, 337 (1956).

shown as × in Fig. 2 fall very well along the curve derived from the present experiments in N_2.

Differential W Values

In the above sections the variation of W has been considered, where W represents a mean value taken over all alpha energies between the initial energy and zero. Of even more interest perhaps is a consideration of the variation of w, defined by $\Delta E/\Delta I$, where ΔE is a small increment of energy loss at some point along the alpha particle track, and ΔI is the corresponding increment of ionization accompanying this loss.

In the determination of this differential w from the present results, the value ΔE may be taken as the difference in energy between any two window combinations designated in column one of Table II. Column 2 gives the transmitted alpha energy for the first window, column 3 that for the second, both taken from column 4 of Table I. The energy difference ΔE is listed in column 4 of Table II.

Similarly, differences in ionization ΔI values may be computed from the ionizations listed in columns 6 and 9 of Table I for the various window combinations taken in pairs. Such ΔI differences are shown for C_2H_4 in column 5, Table II, and for N_2 in column 7. The values of w, defined from the ratio $\Delta E/\Delta I$, appear in columns 6 and 8 of Table II for C_2H_4 and N_2, respectively.

Largely as a matter of convention, in taking energy differences in Table II the energy of the polonium alpha for no window has been assigned its full value of 5.3007 Mev. In computations in Table I the effective polonium alpha energy was taken as 5.291 Mev because of the loss of energy within the collimator holes of the standard source. To accord with the higher energy value now used, in the computations of Table II the corresponding ionization values in C_2H_4 and N_2 for no window were taken directly from the mean absolute values in Table II of reference 5. Since these have already been corrected for collimator losses, they correspond to ionization from an alpha particle of full energy 5.3007 Mev.

As before, the two series of measurements were computed as independent experiments. However, in order to prevent the table from becoming inordinately long, only the mean values for the two series have been recorded there. The individual values for each series may, of course, be readily computed from the detailed data in Table I.

The final agreement of w values for the two independently computed series is still good. The values for either series seldom differ from the means shown in Table II by more than one-half percent. However, such derived values lack the very high precision of the original measurements in Table I. This must obviously be the case, since in any small difference derived from two large quantities the percent errors must be greatly enhanced. This enhancement of errors in the differences constitutes one of the principal difficulties in the determination of w values by this method. (See page 15 of reference 5).

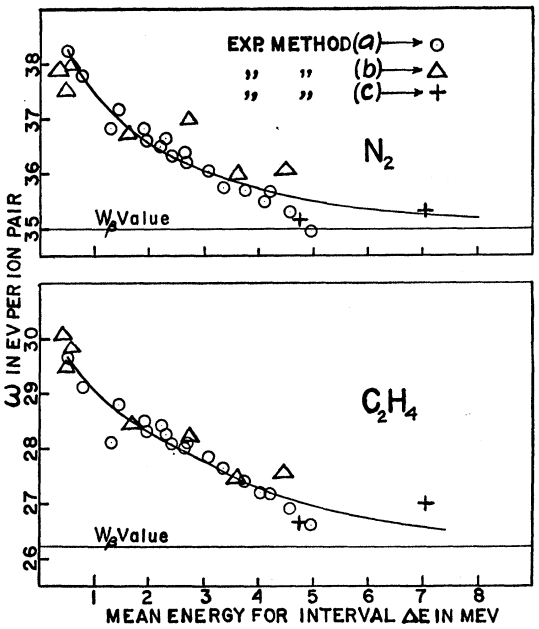

FIG. 3. The differential W value in N_2 and C_2H_4 plotted against the corresponding alpha-energy for the interval ΔE.

The results for w shown in Table II have been plotted as ordinates in Fig. 3 against the corresponding mean energy for the interval ΔE. The latter was considered the mean of the initial and final alpha energies shown in columns 2 and 3 of Table II. Values corresponding to all window combination differences in column 1 were included in the plot.

For the sake of completeness all the W values from Table I have been replotted in Fig. 3. Here W and w are the same, ΔE is equal to the initial alpha energy, and since the final energy is zero, the mean energy for the plot is taken as one-half the initial energy. Such w values, derived from Table I, are probably more precise than many of those in Table II. However, one may advance the objection that, where ΔE is very large, the process of averaging may tend to smooth out the derived curve and hence to obscure possible finer details in it.

In Fig. 3 as in previous figures, the corresponding W_β value is indicated by a horizontal line. The w results for N_2 from current comparisons by method (b) have again been determined and plotted directly. The values for CH_4 have here been modified for comparison with the results from method (a) in C_2H_4 by multiplying all CH_4 ordinates by the factor 26.2/27.25, now representing the ratio of W_β in C_2H_4 to that in CH_4.[7] This alteration of the ordinate scale has the effect of bringing the W_β line for CH_4 into coincidence with that for W_β in C_2H_4. With such an altered scale the experimental w_α values for CH_4 by method (b) show a satisfactory agreement with the results in C_2H_4 by method (a). Such agreement is

not unexpected, since it has already been shown[10] that within a given group of gases, such as the hydrocarbons, the ratio (W for Poα/W_β) is almost constant.

Finally, to the plot in Fig. 3 have been added, as +, the results of method (c) given in Table III. The w values for the energy intervals indicated are shown in columns 6 and 10. Such w values are obtained as in Table II by dividing the above energy differences by ion pair differences as derived from column 3 with columns 4 and 8.

DISCUSSION

With the possible exception of one unexplained high point in N_2 by method (b) at about 2.75 Mev (Fig. 3), the results for the three methods of measurements shown in the figures agree as well as could be expected, if one considers the difficulties which underlie such measurements.

In each curve in Fig. 3 one sees a continuous decrease of the ordinate values with increasing alpha energy. The differential w_α values are seen to approach the W_β values as the alpha energy increases. One gains the impression, however, that these w_α values do not quite sink to the level of the W_β values within the range of alpha energies so far investigated but remain slightly above this value. With the scarcity of experimental points at the higher energies, however, such a conclusion cannot be stated at present with entire certainty.

No satisfactory explanation can at present be made for this apparently continuous decrease in W in polyatomic gases with increasing alpha energy. One can, however, rule out here certain explanations which have often in the past been advanced to account for changes in W values.

One such process often invoked is that of capture and loss of electrons by the alpha particle along its path. Since, however, capture and loss of electrons is negligible except for energies within 1 Mev of the end of its path, such an explanation would seem inadequate to explain changes in W which occur here at much higher energies.

A second explanation, often advanced to explain alterations in W, is the effect due to loss of energy through nuclear collision processes, where energy is transferred to an atom as a whole to be expended in nonionizing effects. These collision processes are particularly important for massive particles such as recoil particles and fission fragments.

Here again, such collisions are most frequent at the end of the alpha path, and it is doubtful whether their effect could explain the continuous decrease in W values found here at relatively high alpha energies. In addition, the fraction of energy lost by such processes should depend, according to simple theory, principally upon the atomic numbers of the particle and the gas. It is thus difficult to see why a gas such as N_2 should show a much more marked effect in such collision interactions with an alpha particle than does argon. It should be noted that, since the W measurements for Figs. 2 and 3 were in the main made relative to argon as a standard gas, any changes of W with energy noted here are over and above any possible similar changes which may occur within argon itself.

From the above considerations, there would seem as yet no plausible theoretical explanation for the continuous change in W values with alpha energy observed here. Some very interesting ideas have been advanced in this general connection by Platzman,[11] but as yet these must be regarded as in some degree speculations.

The Ratio W_α/W_β

A very interesting ratio is that given by W_α/W_β, the existing ratio in any particular gas between the value of W for alpha and beta particles. The ratio is of particular interest in that it strikingly typifies the marked difference in the behavior of the W values for the class of gases including the noble gases and hydrogen on the one hand, and, on the other hand, the class including all other gases which have so far been carefully investigated. From the relative ordinate values in Fig. 2 for an alpha particle of initial energy of 1 Mev, W_α is found to be about 9% greater than W_β in N_2 and 13% greater in C_2H_4. For the alpha particle of 5.3 Mev, the corresponding W_α values are about 4% and 7% greater than W_β. It should be noted that no change in the absolute value of W_β greater than the experimental error has been so far detected in recent experiments for beta rays, ranging in mean energy from 3 to 50 kev.[10,12]

The behavior of the ratio W_α/W_β in the noble gases and hydrogen has been found to be strikingly different. Throughout the somewhat limited range of particle energies which have so far been carefully investigated, there is good evidence to show that the above ratio has always the value of unity. Such evidence has been presented before, but, since the experimental results are widely scattered over a number of papers, a compilation of these results would seem of value here.

Such a compilation is shown in Table IV, which shows as a particular case a comparison of W_α in pure argon for alpha particles of energy about 5.3 Mev with W_β values in pure argon for beta particles of mean energies ranging from 40 kev to 1 Mev. In column 1 are listed from the literature four of the most reliable values for the absolute value of W_α in pure argon for alpha energies of the order of 5 Mev. The first and last values apply to measurements with polonium alpha particles (5.3 Mev) and the other two to measurements with alphas from Pu^{239} (5.15 Mev). The mean of these four determinations has a probable error of not more than $\frac{1}{2}$%. Similarly, for W_β the first four determinations in column 4 give abso-

[10] W. P. Jesse and J. Sadauskis, Phys. Rev. **107**, 766 (1957).

[11] Robert L. Platzman, Nuclear Science Series, Rept. 29, National Academy of Sciences and National Research Council, Publication 752.

[12] J. M. Valentine, Proc. Roy. Soc. (London) **A211**, 75 (1952).

TABLE IV. A comparison of W_α and W_β in pure argon.

Absolute values of W_α in pure argon for alpha energy of 5 Mev, ev/ion pair	W_β Determinations					
	Gas	Mean beta energy	Absolute W_β value (ev/ion pair)	Measured ratio of ionization in gas to ionization in argon	W_β in argon derived from columns 4 and 5 (ev/ion pair)	Ratio W_α/W_β
26.4[a]	air	1 Mev	33.9[e]			
26.3[b]	air	49 kev	33.7[f]			
26.6[c]	air	49 kev	33.6[g]			
26.25[d]	air	49 kev	33.9[h]			
Mean 26.39			33.78	0.777[i]	26.25	1.005
	N_2	49 kev	35.0[h]	0.754[i]	26.4	
	C_2H_6	49 kev	24.6[h]	1.065[i]	26.2	
	C_2H_2	49 kev	25.7[h]	1.019[i]	26.2	
	CH_4	49 kev	27.3[h]	0.967[i]	26.4	
	C_2H_4	49 kev	26.2[h]	1.008[i]	26.4	
	Mean				26.3	1.003

[a] W. P. Jesse and J. Sadauskis, Phys. Rev. **90**, 1120 (1953).
[b] J. Sharpe, Proc. Phy. Soc. (London) **A65**, 859 (1952).
[c] T. E. Bortner and G. S. Hurst, Phys. Rev. **93**, 1236 (1954).
[d] W. Haeberli, P. Huber, and E. Baldinger, Helv. Phys. Acta **26**, 145 (1953).
[e] J. Weiss and W. Bernstein, Phys. Rev. **98**, 1828 (1955); **103**, 1253 (1956).
[f] Z. Bay, W. B. Mann, H. H. Seliger, and H. O. Wycoff, Radiation Research **7**, 558 (1957).
[g] W. Gross, C. Wingate, and G. Failla, Radiation Research **7**, 570 (1957).
[h] See reference 7.
[i] See reference 10.

lute values in air. The first is for mean beta energies estimated at about 1 Mev. The last three are for determinations with the beta particles from S^{35} of mean energy 49 kev. These determinations were made by a great variety of methods and the mean W_β value is probably accurate to within 1%.

In column 5 are listed experimental values obtained for the ratio of the ionization in the gas in column 2 to that in pure argon under identical conditions. This ratio is a mean value from relative determinations with the beta particles from tritium, Ni^{63}, and C^{14}. From these ionization ratios the corresponding W_β value in argon shown in column 6 may be derived from a multiplication of columns 4 and 5. Finally, the ratio W_α/W_β in column 7 may be determined by a division of the results of column 6 into those of column one.

In the top half of Table IV the mean of the four absolute W_β measurements in air has been used to derive by the method of calculation indicated a value of W_β in argon of 26.25 ev/ion pair. In the lower part of the table similar calculations from absolute W_β values for the five gases listed have been made to derive a mean W_β in argon of 26.3 ev/ion pair. The ratios W_α/W_β in the last column for the two determinations differ from unity by 0.5 and 0.3%. Such a deviation is well within the value to be expected from the magnitude of the errors in the original absolute W_α and W_β measurements.

Thus, well within experimental error, the value of W_β for the beta energies so far investigated is seen in Table IV to be identical in pure argon with that for W_α for polonium alpha particles. This is to be compared with a difference of 4% in N_2 and 7% in C_2H_4. The fact that W_β is identical with a value for W_α for one alpha energy does not, of course, show rigorously that such an identity exists for every alpha energy. However, since there is nothing unique in the energy 5.3 Mev for the polonium alpha particle, such a generalization does not seem too improbable. Thus, the results in Table IV are in good accord with our original findings[1] as to the constancy of W in pure argon with alpha particle energy.

It should perhaps be noted at this point that the above measurements are at variance with a large mass of experimental data obtained with gridded pulse chambers. In such experiments only the electronic component of the ionization produced is collected, and the resulting transient pulse is amplified and its relative height measured. In order to facilitate such collection of electrons, to the argon in the chamber there is usually added some five to six percent of CO_2 or CH_4.

Experiments of this sort are perhaps best typified by the high precision measurements carried out during the past ten years by the group at Chalk River. A resumé of such experiments has recently appeared.[13] For the gaseous mixtures used, the value of W is not found to be constant but varies according to the suggested empirical relation

$$W = W_\infty(1+0.069E^{-\frac{1}{2}}).$$

Here E denotes the initial energy of the alpha particle in Mev, and W_∞ is a limiting value of W obtained for alpha particles of very high energy.

The variation in W value as a function of alpha energy predicted by this formula is much greater than any observed in very pure argon under our own experimental conditions, where the total collection includes both positive and negative ions. In fact, the predicted variation in argon is more closely in agreement with the variation actually observed for N_2 in Fig. 2.

[13] G. C. Hanna, in *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley & Sons, Inc., New York, 1953), Vol. III.

The discrepancy between the two methods is exemplified by the following considerations:

The close agreement in the shape of the curve for N_2 in Fig. 2 with the Ishiwari values in air, designated by ✕ in the figure, has already been pointed out. The Ishiwari relative values do not in any way depend upon a comparison with argon. Since our W values in N_2 are relative to ionization measurements in argon with W assumed constant, they must be corrected according to the Chalk River formula, should the W variation in our argon predicted by the formula exist without our knowledge. If one starts then with a point of reference at 5.3 Mev, such a correction procedure raises the W values in N_2 at lower alpha energies. Thus, at 1.0 Mev this rise amounts to almost 4% and thus destroys any semblance of agreement between our own and the Ishiwari curve.

Again, the formula predicts in the gas mixture used a value of W_∞ at high alpha energies 3% lower than that for the polonium alpha energy at 5.3 Mev. Since in this field experiments consistantly show that the beta particle ionizes in gases at least as efficiently and generally more efficiently than the alpha particle, it is hard to see how the W_∞ even at high energies would be smaller than W_β. This would seem to set an upper limit for W_β. Thus by inference, W_β according to the formula should be at least 3% less than the W for the polonium alpha—in conflict with the results in Table IV. It is, of course, possible that such a discrepancy merely exemplifies the limitations in the formula in extrapolation to such large energies.

Examples such as the above merely serve to emphasize the consistent incompatibility of the present results with those obtained by the method of the gridded pulse chamber with gaseous mixtures. At the moment no very valid reason can be advanced to explain this discrepancy.

CONCLUSIONS

The general conclusions of the present paper can hardly be summarized better than by a repetition of two postulates, advanced some five years ago,[4] which predict the interrelation of W_α and W_β. These postulates may be quoted as follows:

"1. If in the relation W_α/W_β = constant for hydrogen and the noble gases, we assume this constant to be unity, then W in these gases is the same both for beta and alpha particles throughout all ranges of energy for either so far measured by us.

"2. In all other gases so far measured, W_α/W_β is not found to be constant. The variation in the ratio seems to come from a variation of W_α with alpha-particle energy rather than a variation of W_β with beta-particle energy. As the alpha-particle energy increases, this ratio probably approaches a constant value, which again is probably unity."

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