ON THE GEIGER-NUTTALL RELATIONSHIP*

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ABSTRACT. It is shown in the present work that the Geiger-Nuttall relationship is more satisfactory and refined when the log λ, E curve is plotted for isotopes having the same atomic number Z. From the theoretical study of α-emission it has been shown that only points, referring to nuclei having the same atomic number, fall on a continuous curve. Even in this case there appears to be some deviation of the actual curve from the theoretical one on both ends (for nuclei having shortest and longest lives). The experimental data of all α-active nuclei have been systematically studied and the modified Geiger-Nuttall curves have been drawn for all elements from Bi to Pu. The α and β stability considerations are used to predict the probable α or β activities as yet unknown. Some of the nuclei suspected of weak α-activity are UX_1^{234}, $MsThI^{228}$ and UY^{231}.

INTRODUCTION

The Geiger-Nuttall relation, $\log \lambda = a + bE$, which was first obtained from empirical data has played a very fundamental part in the understanding of nuclear phenomena. It was the basis of Gamow's famous work on the escape of α-particle through potential barriers.

The latest position of this famous relation is given in Gamow's "Structure of Atomic Nuclei," p. 86. As given there, the (log λ, E) curve for three radioactive series is not a continuous one but it is shown to consist of three distinct ones corresponding to the U, AcU and Th series. Even the curve for a single series, *e.g.*, for Ac is not continuous. When these curves were compiled the half-lives and energies of some of the products particularly the extremely short-lived and extremely long-lived ones were not very accurately known. But recently much more data on these points have been obtained and the series have been prolonged and it appears advisable to re-examine the whole question. The present work has been undertaken with the point in view.

Recently Berthellot (1942) suggested that the points on the Geiger-Nuttall diagram (log λ, E curve) fall on a continuous line if the data belong to nuclei having the same charge number Z. This has been verified by Broda and Feather (1947) in case of Po and led to the interesting discovery that RaE, well-known for its β-activity is also slightly α-active. The ratio of α-activity to β-activity is found as $\sim 10^{-7}$ to 1.

* Communicated by Prof. M. N. Saha.

THEORETICAL BACKGROUND

The object of the present work is to examine critically whether the Geiger-Nuttall curve, log λ against E, is a smooth one only when α-active isotopes of the same atomic number are plotted. Let us now interpret the above assumption of constancy of atomic number Z, in Geiger-Nuttall law from theoretical point of view.

The phenomenon of spontaneous α-radioactivity was first explained by Gamow (1929) and Condon and Gurney (1929) who calculated the transmission factor of the potential barrier by the application of wave-mechanical method. Since then a large number of investigators have attacked this problem assuming different types of potential field in the nucleus. These results differ in the method of attack and the degree of accuracy of the results, but the main term in the transmission factor is the same as given by Gamow.

The disintegration constant λ is calculated from the transparency of the potential barrier either by the semi-classical argument by Laue (1929) or by the assumption of complex eigen-values as is done by Gamow (1937). The form of the potential barrier is assumed to be an inverse square field up to a distance r_0 and a rectangular hole of potential U for distance less than r_0. The transparency factor, calculated by Saha (1944) and Laue's semi-classical arguments yield the relation :

$$\lambda = \frac{v}{r_0} e^{-2k} \qquad \ldots \quad (1)$$

where v = velocity of the α-particle

r_0 = radius of the nucleus $Z-2$.

$$2K = \frac{16\pi e^2(Z-2)}{hv}(u_0 - \sin u_0 \cos u_0)$$

$$u_0 = \cos^{-1}\left[\frac{mv^2 r_0}{4e^2(Z-2)}\right]^{\frac{1}{2}}$$

Using the complex eigen function method, the following relations are obtained between λ and E, for $l=0$ (Preston, 1947)

$$\mu = -\tan u_0 \tan(\mu k r_0) \qquad \ldots \quad (2)$$

$$\lambda = \frac{2v}{r_0} \frac{\mu^2 \tan u_0}{\mu^2 + \tan^2 u_0} e^{-2k} \qquad \ldots \quad (3)$$

where $\mu = (1 - U/E_a)^{\frac{1}{2}}$, $k = \frac{2\pi mv}{h}$

It can be easily seen that if we have $U=0$, $\mu=1$, the equation (3) reduces to

$$\lambda = \frac{v}{r_0} \sin 2u_0 . e^{-2k} \qquad \ldots \quad (4)$$

This expression has been used by Sexl (1933). Thus three expressions for λ are available.

$$\lambda = \frac{v}{r_0} e^{-2k}$$

$$\lambda = \frac{v}{r_0} \sin 2u_0 . e^{-2k}$$

$$\lambda = \frac{2v}{r_0} \cdot \frac{\mu^2 \tan u_0}{\mu^2 + \tan^2 u_0} e^{-2k}$$

The factors $\sin 2u_0$, $\frac{2\mu^2 \tan u_0}{\mu^2 + \tan^2 u_0}$, are of the order of unity. The value of λ changes so rapidly with small adjustments in the value of the constant r_0 in e^{-2k} that the multiplying factor is not of much consequence.

In these calculations the effect of relative motion of the $Z-2$ nucleus is to be taken into account. So we are to use total energy $E = E_\alpha \left(1 + \frac{m_\alpha}{m_r}\right)$, relative velocity of α-particle $v = v_\alpha \left(1 + \frac{m_\alpha}{m_r}\right)$ and reduced mass $m = \frac{m\, m_r}{m_\alpha + m_r}$ in place of E_α, v_α and m_α respectively.

Using the first formula, (1),

$$\log_{10}\lambda = \log_{10} v - \log_{10} r_0 - .4343\gamma[u_0 - \sin u_0 \cos u_0] \quad \ldots \quad (5)$$

where $\gamma = \frac{16\pi e^2 (Z-2)}{hv}$,

$$\log \gamma = 9.2476 + \log (Z-2) - \log v$$

$$u_0 = \cos^{-1}\left\{ \frac{mv^2/2}{2e^2(Z-2)/r_0} \right\}^{\frac{1}{2}}$$

$$2 \log \cos u_0 = 6.8549 - .4343 \frac{m_\alpha}{m_r} + \log r_0 + 2 \log v - \log (Z-2)$$

From relation (5), we see that $\log \lambda$ depends not only on the velocity of the ejected α-particle but also on the atomic number $(Z-2)$ and the nuclear radius r_0. So in general case it can not be represented in a two dimensional graph. The curve, $\log \lambda$ against E, is approximately valid if $(Z-2)$ is kept constant since the variation of r_0 is small from one isotope to other ones. The nuclear radius r_0 may be assumed to vary as the cube root of mass number of the nucleus.

The reason why Geiger-Nuttall could get a more or less smooth curve by plotting $\log \lambda$ against E, is, as pointed out by Gamow (1937, p. 104), due to the fact that variation of Z, E and r_0 in a radioactive series is practically

monotonic as we go down the series. Anomalies occur in the original Geiger-Nuttall curve where this regularity breaks down. Thus the Geiger-Nuttall curves with constant Z, will be more refined and less susceptible to anomalies.

The validity of the theoretical relation could be examined if the theoretical curve of log λ against E for constant Z, could be drawn and compared with the experimentally observed ones. But unfortunately this cannot be directly done since the above relation contains three variables λ, E and r_0, of which λ and E are known experimentally. The other terms, the nuclear radius r_0 cannot be determined as yet from any other independent observation. Hence what is done in this case for verifications is to see whether the values of r_0 calculated from the theoretical relation with the help of experimentally observed values of λ and E, are consistent for different nuclei. As it has been shown by different investigators, (Gamow 1937, Preston 1946, 1947) that the value of r_0 is more or less consistent excepting for the actinium series. For other nuclei r_0 nearly follows the relation $r_0 = RA^{\frac{1}{3}}$ obtained from liquid drop model. No satisfactory explanation is at present available for the abnormally low values of r_0 for ThC$\rightarrow$ThC″, RaC$\rightarrow$RaC″ and AcC$\rightarrow$AcC″.

As the experimental curves are plotted as log λ against E (in MeV) let us transform the equation (5) in terms of energy in MeV. For numerical calculation we use the relation

$$\log \lambda = 21.8428 + \tfrac{1}{2}\log E_v + .217\frac{m_a}{m_r} - \log r_0$$

$$- 1.104\frac{Z-2}{E_v^{\frac{1}{2}}\left(1+\frac{m_a}{m_r}\right)^{\frac{1}{2}}}\cos^{-1}\left[.5896\frac{E_v^{\frac{1}{2}}r_0^{\frac{1}{2}}}{(Z-2)^{\frac{1}{2}}}\right] + .6504\frac{(Z-2)^{\frac{1}{2}}r_0^{\frac{1}{2}}}{\left(1+\frac{m_a}{m_r}\right)^{\frac{1}{2}}}$$

$$- .1131\frac{r_0^{\frac{3}{2}}}{(Z-2)^{\frac{1}{2}}\left(1+\frac{m_a}{m_r}\right)^{\frac{1}{2}}}E_v \qquad \ldots (6)$$

where E_v = disintegration energy in MeV.

r_0 = radius in 10^{-13} cm. units.

The relation (6) exhibits explicit dependence of log λ on the disintegration energy E, charge number $Z-2$ of the product nucleus and radius r_0. Since r_0 varies as $A^{\frac{1}{3}}$, the effect of variation of r_0 from one number to other will be small; but if Z varies for different members, the variation will be much pronounced. So constancy of Z becomes a necessary condition for a two dimentional curve.

The Geiger-Nuttall law has been stated as

$$\log \lambda = a + bE \qquad (7)$$

But the actual theoretical relation is much complicated as seen from the relation (6). As it will be seen in later section that Po contains largest number of α-active isotopes, the theoretical relations deduced above can be conveniently compared with experimentally observed values. Taking an average value of $r_0 = 8.63 \times 10^{-13}$ cm. (for Po^{216}, ThA) ,the following theoretical relation for Po is obtained from the relation (6).

$$\log \lambda = a - \frac{b}{E_v^{\frac{1}{2}}} \cos^{-1}\left(cE_v^{\frac{1}{2}}\right) + d \log E_v - e E_v$$

$$= 38{\cdot}0664 - \frac{89{\cdot}71}{E_v^{\frac{1}{2}}} \cos^{-1} .1923 E_v^{\frac{1}{2}} + \tfrac{1}{2}\log E_v - .3225E \qquad (8)$$

With relation (8) the theoretical curve given in Fig. (1 *a*) is drawn. The curve passing through experimental points is given in Fig.1 (*c*). The agreement with the experimental curve (*c*) is seen to be satisfactory, in the middle part from (214) to (218) but on both sides the theoretical curve diverges from the experimental one. However instead of taking r_0 constant for all isotopes we can take the variation of r_0 from one isotope to other into account according to the relation, $r_0 = R.A^{\frac{1}{3}}$ Thus another theoretical curve (*b*) (Fig. 1)

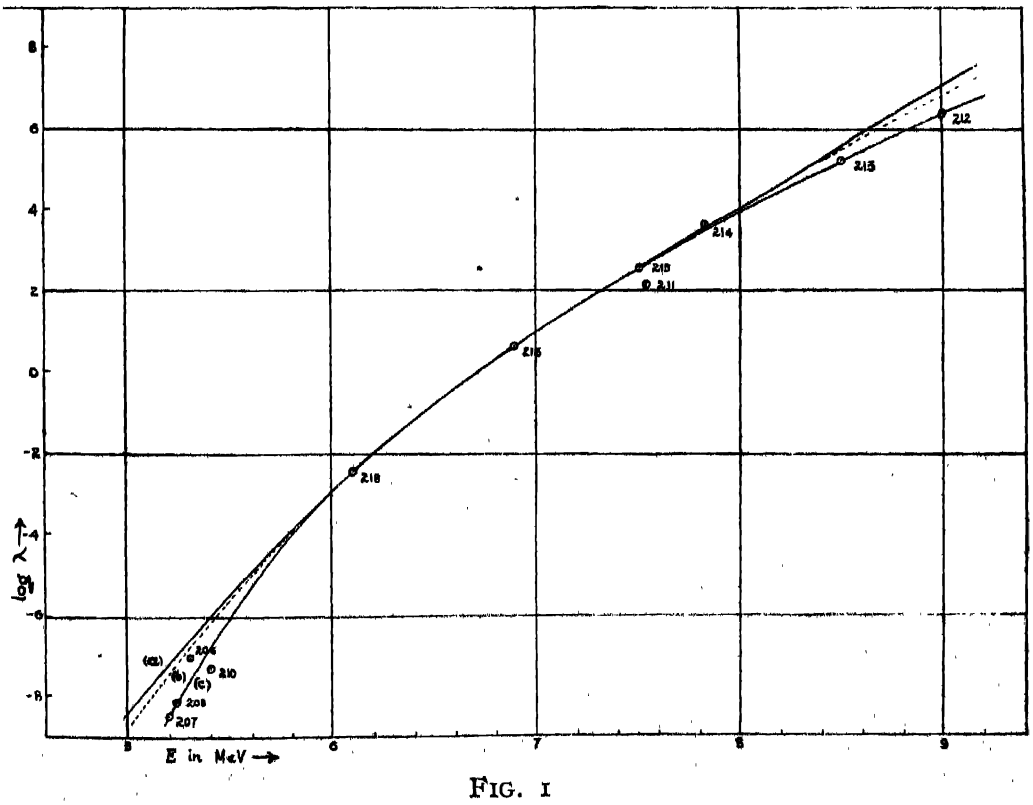


FIG. 1

is drawn from relation (6). The curve (*b*), approaches the experimental curve (*c*) at the end; but discrepancy still remains at the two ends, which shows that the theory of α-particle emission fails to account for very short lived products as well as very long-lived ones.

EXPLANATION OF THE METHOD.

Now the modified Geiger-Nuttall curves are to be drawn for each element starting from Bi. For dealing with the large amount of data we have made use of the nuclear chart originally given by Saha, Sirkar and Mukherjee (1940). The usefulness of this chart has been extended by the work of Saha and Saha (1946) and others on "Nuclear Energetics and β-activity". The part of the diagram dealing with our work is reproduced in Fig. 2.

As the chart shows all α-radio-activity appears to cease with Pb (82). This means, that the activity is too small to be measured. But from 83 onwards, α-activity has been found in many nuclei. Some of these nuclei are also simultaneously β-active and it is possible that, many of which have been found so long only γ- or only β-active may be found, as has been found by Feather in the case of RaE, to show the other type of activity on a very much feebler scale. We have therefore made use of our criterion for β-activity as given by Biswas and Mukherjee (1948) for dealing with each individual cases.

The correct determination of the data namely λ and E is the most important task. For E we have taken, not the energy with which the α-particle comes out, but the total energy of the reaction. As is well-known, this is given by the formula

$$E = E_0 \frac{A}{A-4}$$

In the case of a nucleus which decays both ways by α-disintegration, β-decay or K-capture, experiments give us only the composite life T. As is well-known

$$\frac{1}{T} = \frac{1}{T_\alpha} + \frac{1}{T_\beta}.$$

When we are considering λ, E relation for α-rays, we require T_α. To obtain this we must know the second relation, the ratio of $\frac{T_\alpha}{T_\beta} = \frac{\lambda_\beta}{\lambda_\alpha}$, which gives the ratio of the particles disintegrating by β-decay to that by α-decay. In many cases this ratio is known but in many cases we need have recourse to surmise. These points will be discussed in the proper places.

EXCITED STATES IN α-EMISSION:

It is well-known that many α-active nuclei do not emit α-particles of one energy, but α-particles of several energy groups are found. This is due to the formation of excited states of the initial or the product nucleus in α-emis-

The nuclei emitting complex α-spectra can be divided into two classes.

TABLE I

Bismuth (8_3)

Isotopes	Observed half life	$\frac{\alpha}{\beta}$ ratio	α-half life	λ_α (sec^{-1})	α-Energy, E_α (Mev)	Decay energy, E (Mev)	Produced by	Remarks
Bi^{204}	12h (K-cap) (H_4)	...	...	...	...	...	Pb^{204} (d, 2n) Tl^{203} (α, 3n) (H_4, T_1)	...
Bi^{205}	?	...	...	...	...	...	Pb^{206}(d, 3n) ? (T_1)	K-capture expected
Bi^{206}	6·4d (K-cap) (H_4, T_1)	...	...	...	...	...	P_0^{206} K-cap. Tl^{205} (α, 3n) Pb^{206} (d,2n) Pb^{207} (d,3n) (T_1)	...
Bi^{207}	?	...	...	...	...	...	Pb^{207} (d,2n) ? P_0^{207} K-cap (T_1)	K-capture and α-activity expected.
Bi^{208}	?	...	...	...	...	...	Bi^{209}(n,2n) ? (H_4)	K-capture and β^--activity expected
Bi^{209}	Stable (100%)	...	...	...	...	...	...	
Bi^{210} (RaE)	5d (C6)	$\frac{10^{-7}}{1}$ (B_4)	1.37×10^5y	$1{\cdot}60 \times 10^{-13}$	4·87 (B_4)	4·975	RaD β^- decay	...
Bi^{211} (AcC)	2·16m (C6)	$\frac{99{\cdot}68}{32}$ (C6)	2·166m	$5{\cdot}33 \times 10^{-3}$ $\lambda_{a0} = 4{\cdot}78 \times 10^{-3}$	6·619 (H_3)	6·747	AcB β^- decay	...
Bi^{212} (ThC)	60·5m (C6)	$\frac{35}{65}$ (K_3)	2·99h	$6{\cdot}44 \times 10^{-5}$ $\lambda_{a0} = 1{\cdot}75 \times 10^{-5}$	6·054 (B_3, H_3)	6·170	ThB β^- decay	...
Bi^{213}	46m (E_1, H_1)	$\frac{98}{2}$ (E_1)	46h	$4{\cdot}18 \times 10^{-6}$	5·86 (E_3)	5·97	At^{217} α-decay	Observations rather preliminary
Bi^{214} (RaC)	19·7m (C6)	$\frac{\cdot 04}{99{\cdot}96}$ (C6)	34·2d	$2{\cdot}35 \times 10^{-7}$ $\lambda_{a0} = 1{\cdot}06 \times 10^{-7}$	5·502 (L_4)	6·608	RaB β^- decay	...

(1) Class I: In this class, the α-particles of maximum energy have highest intensity (group O) and the intensity of other groups are smaller but of the same order as the group O. This is due to the formation of the excited states of the product nucleus. The examples are ThC $\longrightarrow$ ThC″, RaAc $\longrightarrow$ AcX, etc.

In the present discussion, the α-emission between the ground states of two nuclei (group O) are considered. Hence the observed disintegration constant λ_α is to be corrected so as to give partical disintegration constant for the zero group λ_{α_0}. Taking the case of ThC″ $\longrightarrow$ ThC″ we find that intensity of group O α-particles is 27.2% of the total intensity. So λ_{α_0} will be 27.2% of the total λ_α (6.44×10^{-5}). Thus the corrected λ_{α_0} is $1.75 \times 10.^{-5}$

Similar correction is applied for all α-emitters of Class I as will be referred to later on.

(2) Class II: This class includes a few α-active nuclei where the α-particles of lowest energy have the highest frequency and α-particles of higher energy are very infrequent, relative intensity being of the order of 1 in 10^6. This is due to the existence of excited states in the initial nucleus. Only the normal α-particles (group O) are included in this discussion. Since the intensities of other groups of α-particles are very small compared to group O, we can put $\lambda_{\alpha_0} \simeq \lambda_\alpha$ and no correction for the complex spectrum is required.

The examples of this type are ThC′ $\longrightarrow$ ThD, RaC′ $\longrightarrow$ RaD.

(83) *Bismuth*

The isotopes of Bi range from mass number 204 to 214. All the relevant data are given in Table I.

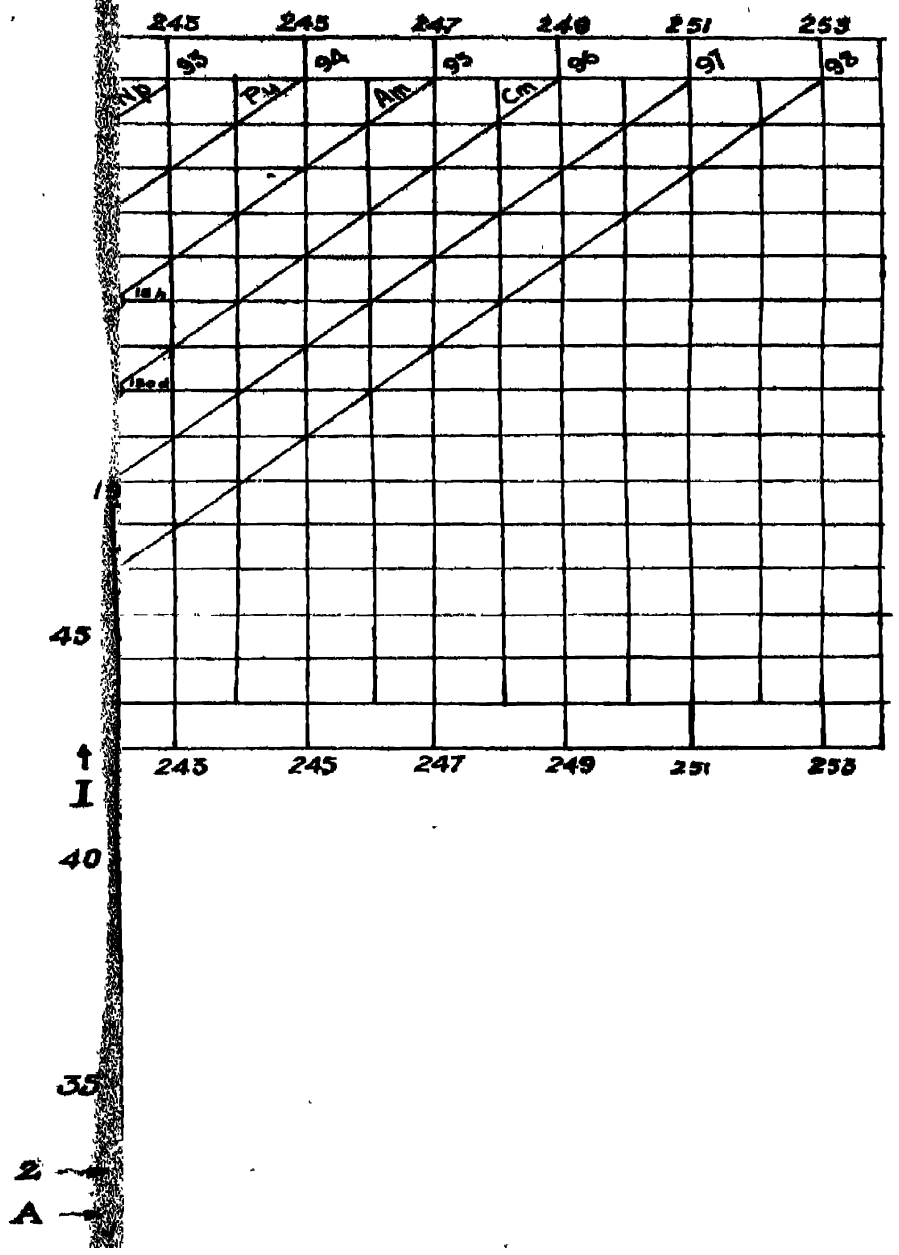
Bi^{204}: This recently obtained isotope of Bi shows a 12 hr K-capturing activity. This is an agreement with the findings of Biswas and Mukherjee (1948) on β-energetics consideration.

Bi^{205}: No distinct activity assignable to Bi^{205} could be found in the reaction expected. It is expected, from the studies of Biswas and Mukherjee (1948) to be a K-capturing nucleus.

Bi^{206}: The 6.4 d K-capturing activity of this nucleus is in agreement with findings of Biswas and Mukherjee (1948).

Bi^{207}: No activity could be assigned to Bi^{207} which is expected in the reaction studied. According to Biswas and Mukherjee (1948) this ought to be a K-capturing nucleus with long life.

Corson *et al* (1940) reports the production of 85^{211} by the reaction Bi^{209} $(\alpha, 2n)$ and showed that it is dually active, 60% being α-active 40% K-active. The product of the α-active branch would be Bi^{207}, but he was unable to trace any activity of Bi^{207}.



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Bi^{208} : The production and mode of decay of this isotope are as yet uncertain. According to Biswas and Mukherjee (1948) it ought to show both K-capture and β^-activity.

Bi^{209} : This is the only stable isotope of Bi.

Bi^{210} : (RaE) : Broda and Feather (1947) have recently shown that in addition to 5 d β-activity, a small fraction of RaE decays by α-activity to Th^{206}. The branching ratio of α and β is estimated as $\sim 1 \times 10^{-7} : 1$. The energy of α-particles has been obtained from the equivalence of energy-release in the two branches as shown in Fig. 3. The value of E_α is to be confirmed by direct experiment. A little alteration in the value of branching ratio and E_α will shift the point on the curve to a small extent.

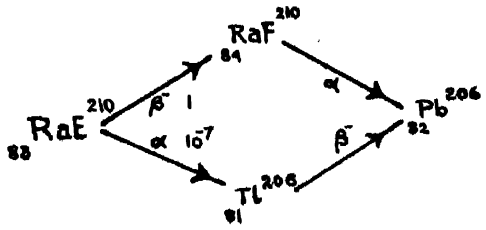

Fig. 3.

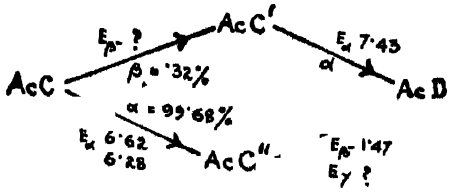

Fig. 4.

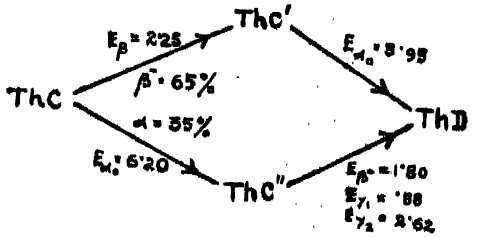

Fig. 5.

Bi^{211} : (AcC) : The dual disintegration scheme of AcC is given in FIG. 4. The main disintegration of AcC is by α-emission (99.68%) to AcC''. Two groups of α-particles are emitted. The complex α-spectra fall in Class I. The intensity of group O α-particles is 84%. Thus $\lambda_\alpha = 5.33 \times 10^{-3}$ sec^{-1} is corrected to give $\lambda_{\alpha 0}$ which becomes 4.478×10^{-3} sec^{-1}. This isotope falls close to the log $\lambda_{\alpha 0}$ curve for Bi.

The energy of the β-emission in AcC$\rightarrow$AcC′ is not yet determined. From the equivalence of energy-release in two branches, $E\beta^-$ comes out as .66 MeV. The study of the disintegration of AcC is not yet complete.

Bi^{212} (ThC) : The dual disintegration scheme of ThC is well studied by Ellis and this is given in Fig. 5. In the α-disintegration branch ThC$\rightarrow$ThC″, the observed composite half-life is resolved to give α-half-life and λ_α. The α-spectra is complex consisting of five components (Class I). The intensity of Group O α-particles in 27.2%, and $\lambda_{\alpha 0}$ is calculated as 1.749×10^{-5} from the value of λ_α (6.439×10^{-5}). This isotope falls on the smooth log $\lambda - E$ curve for Bi.

Bi^{213} : This isotope is the corresponding C-product in the newly discovered $(4n+1)$ radio-active series. The data for branching ratio, composite half-life and α-energy release are taken after the determination of English *et al* (1947). The study of this new series is rather preliminary and further investigation is required.

Bi^{214} (RaC) : The complete disintegration scheme of RaC to RaD has not yet been established. In the disintegration RaC to RaC″ two groups of α-particles having energies of 5.612 and 5.549 MeV have intensities of 45.4% and 54.6%. The α-disintegration constant is calculated from composite halflife ; this λ_α is corrected to give partial disintegration constant $\lambda_{\alpha 0}$ which becomes 1.056×10^{-7} sec^{-1}.

The Refined Geiger-Nuttall Curve For Bi

With the data given in Table I, the Geiger Nuttall plot, log λ against E, is made for the isotopes of Bi (Fig. 6). The points lie close to a smooth curve excepting Bi^{214} (RaC). This curve is somewhat different than that given by Broda and Feather (1947) in the study of α-activity of RaE. The curve given by them is drawn through the points corresponding to α-particles other than the zero group, whereas the present curve is drawn for Group O α-particles of the isotopes of Bi. The α-active isotopes of Bi includes C-products and it has been shown by Gamow (1937) that none of these C$\rightarrow$C″ bodies show normal behaviour.

(84) *Polonium*

Polonium contains largest number of α-active nuclei. Its isotopes range from mass number 206 to 218 with exception of 209 and 217. The relevant data are given in Table II.

Po^{206} : This recently obtained Polonium isotope exhibits simultaneous α-emission and K-capture processes. The K-capture activity of this even-even nucleus is due to its position in the extreme right flank of the I-group. As pointed out by Biswas and Mukherjee, this nucleus is a good confirmation of the Saha-Saha theory (1946).

No daughter of Po^{206} by α-emission has been reported. The product Pb^{202} should be α-active.

TABLE II

Polonium (84)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	λ_α (sec^{-1})	α-energy, $E\alpha$ (Mev)	Decay energy, E (Mev)	Produced by	Remarks
Po^{206}	9d (T2)	$\frac{\alpha}{K}=\frac{10}{90}$ T(2)	90d	$8{\cdot}92\times10^{-8}$	5·2 (T2)	5·3	Pb^{204} (α, 2n) (H4)	...
Po^{207}	5·7h (T2)	$\frac{\alpha}{K}=\frac{\cdot01}{99{\cdot}99}$ (T2)	6·5y	$3{\cdot}38\times10^{-9}$	5·1 (T2)	5·2	Pb^{206} (d, 3n) (H4)	...
Po^{208}	~3y (T2)	...	—3y	$7{\cdot}33\times10^{-9}$	5·14 (T2)	5·24	Pb^{207} (α, 3n) (H4)	...
Po^{209}	?	...	...	...	...	...	Bi^{209}(d, 2n) ? (T2)	K-capture and α-activity expected.
Po^{210}	140d (C6)	...	140d	$5{\cdot}89\times10^{-8}$ (C2)	5·303(C2) 5·298 (H3)	5·405	RaF β^-decay Bi^{209} (d, n) (C_3, H_5)	...
Po^{211} (AcC')	5×10^{-3} s (C6)	...	5×10^{-3} s	$1{\cdot}39\times10^{2}$	7·434 (L_4)	7·543	AcC β^-decay 85^{211} K-cap	...
Po^{212} (ThC')	3×10^{-7} s (D1)	...	3×10^{-7} s	$2{\cdot}31\times10^{6}$	8·776 (B_3, H_3)	8·944	ThC β^-decay	...
Po^{213}	$4{\cdot}4\times10^{-6}$s (E1, H1)	...	$4{\cdot}4\times10^{-6}$s	$1{\cdot}58\times10^{5}$	8·336 (H1)	8·496	Bi^{313} β^-decay (E1, H1)	...
Po^{214} (RaC')	$1{\cdot}5\times10^{-4}$s (D1, R4, W1)	...	$1{\cdot}5\times10^{-4}$s	$4{\cdot}62\times10^{3}$	7·680 (B_3, H_3)	7·827	RaC β^-decay	...
Po^{215} (AcA)	$1{\cdot}83\times10^{-3}$s (W1)	...	$1{\cdot}83\times10^{-3}$s	$3{\cdot}79\times10^{2}$	7·365 (L_4)	7·504	An^{219} α-decay	...
Po^{216} ThA)	·158 s (W1)	$\frac{99{\cdot}086}{\cdot014}$ (K1)	·158s	4·39	6·774 (B_3, H_3)	6·902	Tn^{220} α-decay	...
Po^{217}	?	...	...	...	...	...	...	Not yet known. This will be β^--active.
Po^{218} (RaA)	3·05m (C6)	$\frac{99{\cdot}96}{\cdot04}$ (K2)	$3{\cdot}06_{2m}$	$3{\cdot}77\times10^{-3}$	5·998 (B_3, H_3)	6·110	Rn^{222} α-decay	...

Po^{207} : This also is a simultaneous α and K-active nucleus. The high K-capture process (99.99%) is in agreement with Biswas and Mukherjee's findings. No daughter of Po^{207} is found. Po^{207} will decay to Bi^{207} by K-capture. As given before Bi^{207} should decay by K-capture.

Po^{208} : The 3 year α-activity of Po^{208} is in agreement with the stability rule. According to Biswas and Mukherjee, this even even nucleus should have no β^- or K-capture activity.

Po^{209} : No activity could be assigned to Po^{209} which is expected in the reaction studied, Bi^{209} (d, 2n) Po^{209}. This isotope will decay by K-capture (Biswas and Mukherjee, 1948) as well as by α-activity.

Po^{210} : The investigation of Chang (1946) revealed that Po^{210} (RaF) does not emit homogeneous α-rays, but seven groups of particles are present. The intensity ratios of the higher order groups to the main group are at variance with the present theory of α-emission of excited states. The α-energy of Group O is highest and the relative intensity is 10^6, compared to other groups whose energies are smaller than the main group. Thus the α-spectra do not fall in either of Class I or Class II as stated before. Taking the experimental observation as correct, Po^{210} presents a problem, hitherto unknown and unexplained, in α-emission.

Po^{211} : (AcC′) : The normal α-particles of 7.434 MeV from AcC′ is surely attended by long range α-particles of very low intensity as in the case of ThC′ and RaC′. These have not yet been studied. Accurate determination of the extremely short half-life of AcC′ is required as no recent data are available for this. The α-spectra of AcC⟶AcD should fall in Class II as in other C-products, and hence no correction for λ_a is required.

The absence of β-activity of this nucleus follows from the studies of Biswas and Mukherjee (1948).

Po^{212} (ThC′) : The spectra of ThC′⟶ThD has been completely investigated and with the main group of 8.776 MeV two long range α-particles of very small intensity are present. The complex α-spectra fall in Class II and no correction of λ_a is required. The short half-life (3×10^{-7} sec) has been accurately determined by Dunworth (1939).

No β-activity is possible for this even-even nucleus.

Po^{213} : In the same line with ThC′ and AcC′, this isotope is the corresponding C′ body of the newly discovered (4n+1) radio-active series. The half-life is reported as 4.4×10^{-6} sec. Further investigation is sure to show long range α-particles of very small relative intensity.

No β-activity of this nucleus is possible as shown by Biswas and Mukherjee.

Po^{214} (RaC′) : It has been observed by Lewis & Bowden that twelve long range α-groups of very small relative intensity are present with the main group of α-particles. The number of γ-rays, due to transitions

between these levels, as pointed out by Ellis, should be many more than at present observed. The half-life has been accurately determined by Dunworth (1939), Rotblat (1941) and Ward (1942).

This α-spectra of Class II require no correction for λ_a. The β-stability of this nucleus is accounted for by its even-even property.

Po^{215} (AcA) : The α-spectrum is simple as observed by Lewis and Bowden (1934). The short half-life, 1.83×10^{-3} sec., has been accurately measured by Ward (1942). According to Biswas and Mukherjee *loc. cit.*, low energy β-emission is probable for Po^{215} (AcA). The isotopes, ThA and RaA of two other radioactive series have been observed to emit low intensity β-rays in addition to strong α-activity (Karlik and Bernert, 1943). Thus the predicted β-activity of very weak intensity will be in agreement with the A-products of two other series. This will be worthy of further investigation.

Po^{216} (ThA) : Karlik and Bernert (1943*a*) showed that low intensity β-ray branching (.014%) exists for this strong α-active nucleus. The β-ray energy has not yet been measured. Very low energy β-emission from this even-even nucleus is explained by its position in the flank of the group I=48. This is in confirmation of Saha-Saha theory (1946).

The short half-life (.158 sec) has been accurately measured by Ward (1942).

Po^{217} : This isotope of Po is yet unknown. This should belong to $(4n+1)$ radioactive series ; but 85^{217} is the only known isotope of this mass number in $(4n+1)$ radioactive series. If ever obtained, this will be β^- active of very short half-life.

Po^{218} (RaA) : The investigations of Karlik and Bernert (1943*b*) revealed a low intensity β-ray branching (.04%) for this predominantly α-active nucleus. The β-ray energy has not yet been measured. The β-activity of this even-even nucleus is due to its position in the extreme flank of Group I=50, and is in good agreement with Saha-Saha theory (1946). As indicated by Biswas and Mukherjee, β-ray energy-release is expected to be $\sim .2$ MeV.

The Geiger-Nuttall Curve for Po.

Since Po contains largest number of α-active isotopes, the validity of the refined Geiger-Nuttall relationship can be tested with the data provided by it. The curve, log λ against E, (Fig. 6) is plotted with the data given in Table II. It is observed that almost all the isotopes fall on a smooth curve. Small deviations occur for Po^{211} (AcC'), Po^{210} and Po^{206}. In case of Po^{211} (AcC') it has already been pointed out

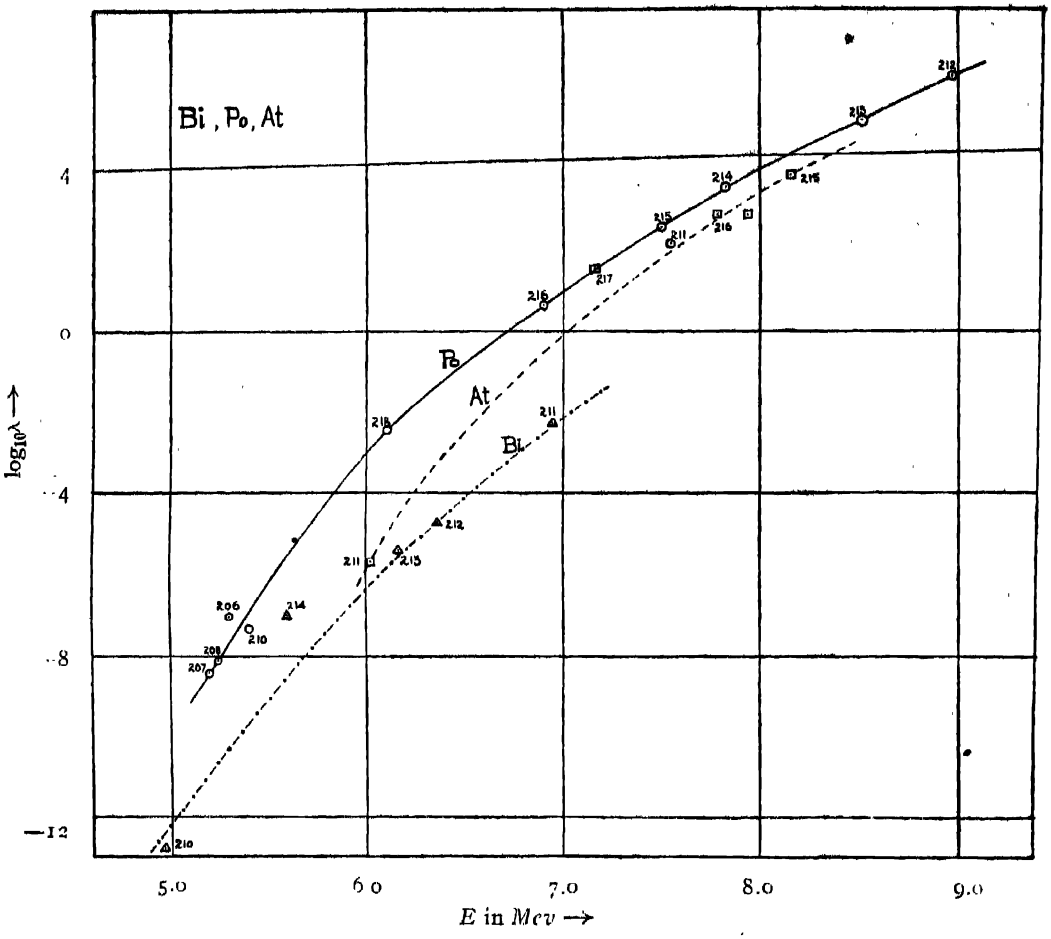

FIG. 6

that the short half-life (5×10^{-3} sec) has not been measured with accuracy in recent years. Po^{210} exhibits a new type of α-activity as indicated before. The data for the other isotope, Po^{206} are rather preliminary. Thus the proposed refinement of the Geiger-Nuttall relation is seen to hold good.

(85) *Astatine*

At present five isotopes of element 85 are known, all of which show α-activity. The data for one isotope is insufficient. The relevant data are given in Table III.

$85At^{211}$: This isotope was obtained in artificial transmutation by 40 MeV α-particles on Bi^{209} by Corson *et al* (1940). The observed *K*-capture activity of this, in addition to α-activity is well explained by the β-energetics for I=41 (Biswas and Mukherjee, 1948).

At^{215} : This isotope is α-active and β-stable. The β-stability of this is in agreement with β-energetics considerations.

TABLE III

Astatine (85)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	λ_α (sec^{-1})	α-energy (MeV)	Decay energy E_t (McV)	Produced by	Remarks
At^{211}	7.5 h (c 5)	$\frac{\alpha}{K} = \frac{60}{40}$	12.5h	1.54×10^{5}	5.94 (c5)	6.03	$Bi^{209}(\alpha, 2n)$ (c5)	α-decay product not yet observed.
At^{215}	10^{-4}s (G 2a)		$\sim 10^{-4}$s	6.93×10^{3}	8.00 (G2a)	8.15	Fr^{219} α-decay	
At^{216}	$\sim 10^{-3}$s (G 2a)		$\sim 10^{-3}$s	6.93×10^{2}	7.64 (G2a) 7.79 (K1)	7.79 7.93	Fr^{220} α-decay ThA^{216} β-decay	Also β^--activity expected.
At^{217}	2.1×10^{-2}s (E1, H1)		2.1×10^{-2}s	33.0	7.02 (E1, H1)	7.16	Fr^{221} α-decay	
At^{218}	Few Sec? (K2)				6.63 (K2)	6.75	RaA^{218}β-decay	Data incomplete.

$85At^{216}$: This isotope is formed in weak β^--branching of ThA (Karlik and Bernert, 1943*a*) and by α-decay of Fr^{220}. The half-life is stated as $\sim 10^{-3}$s. The α-energy is given as 7.64 MeV according to earlier determination and 7.97 MeV according to later determination. This is also expected to show β^--activity, but probably this is overshadowed by the more intense α-activity.

$85At^{217}$: This isotope is a member of the newly discovered $(4n+1)$ radio-active series. Its α-activity has been observed, but it may be also β^--active with small energy-release.

$85At^{218}$: This isotope is produced in the β-branching of RaA which is only 0.04%. The value of half-life is uncertain and is given as several seconds. The α-energy is reported as 6.63 MeV by Karlik and Bernert (1943). Further investigation of this isotope is required. Taking the value of E_a as correct, the half-life of At^{218} may be estimated from the Geiger-Nuttall curve for At. This comes out as $\sim$'5 sec.

The Geiger-Nuttall Curve for At.

Of five α-active isotopes of At, the available data permit to plot four of them. As seen in Fig. 6 these lie on smooth log λ, E curve within the limits of experimental error. This curve is similar to that of Po and lies below the latter. This Geiger-Nuttall curve for At is useful to determine half-life from a knowledge of E_a and *vice versa* for any other isotope with incomplete data. Using this curve half-life of At^{218} comes out as $\sim$'5 sec.

(86) *Radon*

All three nown isotopes of Rn are α-active. The relevant data are given in Table IV.

Rn^{218} : This isotope is obtained in the co-lateral chain of Ra-series. The α-energy is not directly obtained from Rn^{218} but is assigned to it in order of half-life.

Rn^{219}(An) : The α-spectra of Rn^{219} is complex consisting of 4 groups. The intensity of the zero group α-particles is 70%. Accordingly the value of λa_0 is .124 sec^{-1}.

TABLE IV

Radon (86)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	λ_α (sec^{-1})	α-energy (MeV)	Decay energy E (MeV)	Produced by	Remarks
Rn^{218}	.019 s (s 12)		.019 s	36.5	7.1 (S12)	7.23	Ra^{222} α-decay	
Rn^{219} (An)	3.92 s (c6)		3.92 s	.17 λ_{a0}=.12	6.82 (H_3)	6.95	AcX^{223}α-decay	
Rn^{220} (Tn)	54.5 s (c6)		54.5 s	1.27×10^{-2}	6.28 (B_3, H_3)	6.40	ThX^{224}α-decay	
Rn^{221}	?							β^--activity expected.
Rn^{222}	3.825 d (c6)		3.825 d	2.10×10^{-6}	5.486 (B_3, H_3)	5.587	Ra^{226}α-decay	

Rn^{220}(Tn) : The α-particles from Tn^{220} are homogeneous as observed by Briggs (1936) and Lewis and Bowden (1934).

Rn^{221} : This isotope of Rn is not yet known. This may be formed if a small α-branching exists in Ra^{225} which is not unlikely. Rn^{221} will be predominantly β^--active.

Rn^{222} : The α-particles of Rn^{222} are homogeneous according to the observation of Lewis and Bowden (1934) and Briggs (1936).

The β-stability of all three known isotopes of Rn follows from the studies of Biswas and Mukherjee (1948).

Geiger-Nuttal Curve for Rn.

With the data given a Table IV, the log λ, E curve is drawn from the isotopes of Rn (Fig. 7). It is seen that the three points lie on a smooth curve

while the one of Rn^{219} falls outside, A redetermination of λ and R_a of Rn^{31} is required.

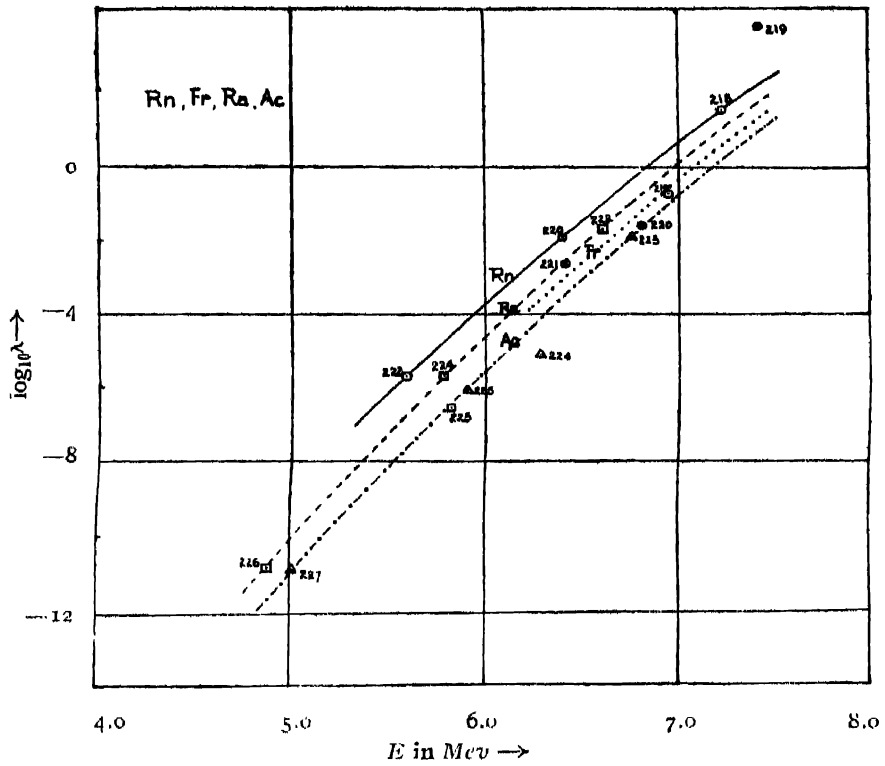

FIG. 7

(*87*) *Francium*

At present four isotopes of element 87 are known of which one is β^--active. The relevant data are given in Table V.

Fr^{219} : This is obtained in a colateral chain of Ac series recently synthesised. As expected this is β-stable.

Fr^{220} : This isotope is observed as α-active. This is expected to be also β^--active.

Fr^{221} : This isotope is a member of the recently discovered $(4n+1)$ radioactive series. The β-energetics curves for $I=47$ shows that this will be β-stable.

Fr^{222} : This isotope is not yet known. This isotope will be β^--active.

Fr^{223} : (AcK) Perey and Lecoin (1939) discovered a small α-activity of Ac^{227}, $\alpha:\beta$ branching ratio being 1 : 99. The α-decay product is $87Fr^{223}$ which is called AcK. This decays by β^--activity to AcX^{223}.

The β^--activity of Fr^{223} is in agreement with the studies of Biswas and Mukherjee (1948). The β^--ray energy of 1.2 MeV is supported by theoretical considerations, but no γ-ray of so high energy, >3 MeV, as reported by them, should exist with this isotope.

TABLE V

Francium (87)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half life	λ_α (Sec^{-1})	α-energy (MeV)	Decay energy, E (MeV)	Produced by	Remarks
Fr^{219}	$\sim 10^{-4}$ s (G2α)		$\sim 10^{-4}$ s	6.9×10^{3}	7.30 (G2α)	7.43	Ac^{223} α-decay	Precise value of λ is required.
Fr^{220}	$\sim$30 s (G2α)		$\sim$30 s	2.3×10^{-2}	6.63 (G2α)	6.81	Ac^{224} α-decay	β^--activity also expected.
Fr^{221}	5 m (F1, H1)		5 m	2.3×10^{-3}	6.31 (F1)	6.42	Ac^{225} α-decay	
Fr^{222}	?							This will be β^--active.
Fr^{223} (AcK)	21m (β^-) (P1, P2)						Ac^{227} α-decay	

Geiger-Nuttall curve for Fr.

As the experimental data are approximate, the point of Fr^{220} and Fr^{221} lie close to the G-N-Curve for Fr, while Fr^{219} lies much above the curve (Fig. 7). Precise experimental values are required for these.

(88) *Radium*

The known isotopes of Ra range from Ra^{222} to Ra^{228} (MsThI) with the exception of Ra^{227}. The useful data are given in Table VI.

Ra^{222}: This is β-stable as expected from β-energetics, and is only α-active. The α-energy has not been obtained from separated isotope but is assigned in order of half-life.

Ra^{223} (AcX): As reviewed by Bethe (1937), the α-spectra of AcX is complex consisting of four groups. The intensity of group zero α-particles is 4%. The observed disintegration constant is used to give λ_{α_0} equal to 2.86×10^{-7} sec.$^{-1}$.

The β-stability of Ra^{223} is explained by β-energetics considerations.

Ra^{224}(ThX): The α-particles of Th^{224} are homogeneous according to the investigation of Briggs (1936).

Ra^{225}: This isotope is a member of the $(4n+1)$ radio-active series. The β^--activity of Ra^{225} is in agreement with the studies of β-energetics. It is a

descendant of 7×10^3 yr α-active Th^{229}. Hence it is plausible that feeble α-activity of Ra^{225} may exist which is masked by a more intense β-activity. The suspected α-activity of Ra^{225} requires further investigation.

Ra^{226} : The α-particles from Ra^{226} are not homogeneous, but belong two groups (Lewis and Bowden, 1934). The intensity of Group O particles is 97.8% from which λ_{α_0} is estimated as 1.35×10^{-11} sec.$^{-1}$

Ra^{227} : This Ra isotope is not yet known. It may be formed if weak α-activity of Th^{231} is detected which is not unlikely. This will show β^--activity according to β-energetics studies.

TABLE VI

Radium (88)

Isotopes	observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half life	$\lambda\alpha$ (Sec^{-1})	α-energy (MeV)	Decay Energy, E (MeV)	Produced by	Remarks
Ra^{222}	38s (S12)	..	38s	...	6.5 (S12)	6.61	Th^{226}α-decay	...
Ra^{223} (AcX)	11.2d (c6)	...	11.2d	7.14×10^{-7}	5.72 (L4)	5.82	$RdAc^{227}$α-decay	Data require redetermination
Ra^{224} (ThX)	3.61d (L_3)	...	3.64d	2.2×10^{-6}	5.68 (B_3)	5.78	$RdTh^{228}$α-decay	...
Ra^{225}	14d (β) (H1, H1)	...	...	...	...	...	Th^{229}α-decay	α activity probable
Ra^{226}	1590y (c6)	...	1590y	1.38×10^{-11} $\lambda_{\alpha_0}=1.35 \times 10^{-11}$	4.79 (L4)	4.88	I_0^{230}α-decay	...
Ra^{227}	?	...	...	...	...	...	...	β^--activity expected
Ra^{228} (MsTh1)	6.7y(β) (c6)	...	...	..	...	...	Th^{232}α-decay	weak α-activity probable

Ra^{228} (MsTh1) : The low energy β^--activity of the even-even nucleus, $_{88}MsThI^{228}$ is in good agreement with Saha-Saha theory as indicated in the β-energetics study of the Group $I = 52$. Since it is the decendant of 1.39×10^{10} yr α-active Th^{232}, it is likely that α-activity also occurs for MsThI with a half-life of the order of a million years which is probably overshadowed by the more intense β^--activity. The probable α-activity of MsThI is to be searched for.

The refined Geiger-Nuttall Curve for Ra.

The plot of the experimental data in Table VI is given in Fig. 7. It is observed that out of four α-active isotopes of Ra, one point Ra^{223} do not fall on the smooth curve. Some anomaly in the experimental data is seen to exist in case of AcX^{223} and ThX^{224}. The α-energy values of these are 5.719

and 5.681 MeV respectively according to spectroscopic determination of Lewis and Bowden (1934) and Briggs (1936). But the disintegration constant λ_α of ThX^{224} having lower α-energy is given as greater than λ_α for AcX^{223}. These data are incompatible with the theory of α-activity. The data for Ra^{223} (AcX) should be re-investigated and revised.

(89) *Actinium*

The isotopes of Ac range from Ac^{223} to Ac^{228} with the exception of Ac^{226}. The relevant data are given in Table VII.

Ac^{223} This should exhibit *K*-capture in addition to observed α-activity.

TABLE VII

Actinium (89)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	$\lambda\alpha$ (Sec^{-1})	α-energy (MeV)	Decay energy *E* (MeV)	Produced by	Remarks
Ac^{223}	~2m (G2*a*)	...	~2m	1.16×10^{-2}	6.64 (G2*a*)	6.76	Pa^{227}α-decay	*K*-capture activity probable.
Ac^{224}	~2.5h (G2*a*)	$\frac{\beta}{K}\sim\frac{1}{10}$	27.5h	7.7×10^{-6}	6.17 (G2*a*)	6.28	Pa^{228}α-decay	Precise data required
Ac^{225}	10d (E_1,H_{11})	...	10d	$8.02\times10^{?}$	5.801 (E_1)	5.906	$Ra^{225}\beta^-$-decay	...
Ac^{226}	...	...	...	⋮	...	...	...	This will be β^--active.
Ac^{227}	13.5y (C6)	$\frac{1}{99}$ (P_1,P_2)	1350y	1.63×10^{-11}	5.0 (P_1, P_2)	5.09	Pa^{231}α-decay	
Ac^{228} (MsThII)	6.13h (C6)	$\frac{\alpha}{\beta}$? (G_5,G6)	...	...	4.5 (G_5,G6)	4.58	$MsThI^{228}\beta$-decay	

Ac^{224} : The observed *K*-capture activity along with α-emission is in agreement with β-energetics considerations.

Ac^{225} : This is a member of the recently discovered (4n + 1) radioactive series. The β-stability of this isotope is in agreement with the β-energetics studies.

Ac^{226}: This isotopes is not yet known. If ever obtained, it will be predominantly β^--active.

Ac^{227} : Perey and Lecoin (1939) discovered that along with strong β^--activity of Ac^{227}, a weak α-activity exists to the extent of 1:99. The β-activity of Ac^{227} is in agreement with β^--energetics studies. The α-branching of Ac^{227} produces AcK, which is an isotope of element 87.

Ac^{228} (MsThII): This predominatly β^--active isotope has been reported to be very weakly α-active by Gueben (1933). The branching ratio, as well

as the α-decay product, Fr^{224} has not yet been observed. The α-energy is reported as 4.5 MeV from range measurement. This nucleus requires further studies.

Taking the α-energy to be correct, the modified Geiger-Nuttall Curve can be used to find out λ_α for Ac^{228}. The α-half-life comes out as 1.5×10^6 years, from which $\alpha : \beta$ branching ratio becomes $5 \times 10^{-8} : 1$.

Modified Geiger-Nuttall Curve for Ac.

Of four isotopes of Ac, three points lie on the smooth G-N Curve for Ac (Fig. 7) only Ac^{224} falls outside. Precise determinations of λ, E_α and $K : \alpha$ ratio are required for Ac^{224}. The unknown data for $MsThII^{228}$ can be roughly estimated from this curve. Taking the α-energy data of MsThII to be correct, the α-half-life and the ratio of $\alpha : \beta$ emissions are calculated as given above.

(90) *Thorium*

The isotopes of Th range from Th^{226} to Th^{234}. Five of them are α-active. The relevant data are tabulated in Table VIII.

Th^{226} : No other activity is expected from β-energetics studies. Th^{227} (Rd Ac) : As observed by Lewis and Bowden (1934) the α-spectra of RdAc is found to be highly complex consisting of eleven α-groups. The spectra is of Class I and the intensity of Group O α-particles is 24%. From this the value of $\lambda_{\alpha 0}$ comes out as 1.018×10^{-7} sec^{-1}.

Th^{228} (Rd'Th) : The studies of Lewis and Bowden (1934) revealed the α-spectra from $RdTh^{228}$ to be complex consisting of two groups. The intensity of Group O α-particles is 85%. The partial disintegration constant $\lambda_{\alpha 0}$ comes out as 9.33×10^{-9} sec^{-1}. Energetically no other activity is probable for this.

Th^{229} : This one is a member of the $(4n+1)$ radioactive series. The experimental data are rather preliminary. Very weak β^--activity is not unlikely from β-energetics consideration.

Th^{230} (Io) : The α-particles are homogeneous. The α-energy value given by Winand (1937) appear satisfactory from the Geiger-Nuttall Curve for Th.

Th^{231} (UY) : The observed β^--activity of Th^{231} is in agreement with energetics consideration. As it is the α-decay product of U^{235} this isotope is strongly suspected to show α-activity with long life like Ac^{227}. This possibly remains masked by strong β^--activity. This requires further studies.

Th^{232} : The energy of α-particles from natural thorium is different investigators. Ionisation chamber measurements by Schintlmeister (1937) give α-energy as 4.2 MeV. Latest determination is due to Faraggi (1936) who

TABLE VIII

Thorium (90)

Isotope	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	λ_α (Sec^{-1})	α-energy (MeV)	Decay energy E(MeV)	Produced by	Remarks
Th^{226}	30.9m (Si2)	...	30.9m	3.74×10^{-4}	6.3 (Si2)	6.41	$U^{230}\alpha$-decay	...
Th^{227} (RdAc)	18.9d (c6)	...	18.9d	4.24×10^{-7} $\lambda_{\alpha\alpha}=1.02\times10^{-7}$	6.049 (L4)	6.156	$Ac^{227}\bar{\beta}$-decay	..
Th^{228} (RdTh)	1.90y (c6)	...	1.90y (c6)	1.10×10^{-8} $\lambda_{\alpha\alpha}=9.33\times10^{-9}$	5.418 (L4)	5.514	$MsThI^{228}$ β-decay	...
Th^{229}	$\sim5\times10^3$y (E1, H1)	...	$\sim5\times10^3$y	4.4×10^{-12}	$\sim$.5 (E1H1)	$\sim$5.09	$U^{233}\alpha$-decay	Data very approximate.
Th^{230} (Io)	8.3×10^4y (c6)	...	8.3×10^4y	2.65×10^{-13}	4.81 (W3)	4.865	$UII^{234}\alpha$-decay	...
Th^{231} (UY)	24.6h ($\bar{\beta}$) (c6)	...	...	...	...	...	$U^{235}\alpha$-decay Th^{232}(n,2n) (N3)	weak α-activity probable.
Th^{232}	1.39×10^{10}y (K3)	...	1.39×10^{10}y	1.58×10^{-18}	4.2 (S6) 3.90 (F1)	4.27 3.97	Natural Source	...
Th^{233}	23m ($\bar{\beta}$) (G4)	...	...	...	...	...	Th^{232}(n,γ) (M2)	...
Th^{234} (UX_1)	24.5m ($\bar{\beta}$) (c6, s4)	...	...	...	...	...	$U^{238}\alpha$-decay	weak α-activity probable.

determined the range of α-particles by photographic method. With the range-energy curve by Holloway and Livingstone (1938), E_α becomes 3.90 MeV. This value appears too low.

Th^{234} : This, being the decay product of long-lived U^{238}, is expected to show weak α-activity which probably remains masked by strong β^--activity.

Geiger-Nuttall Curve for Th.

With the data given in Table VIII a continuous curve can be drawn through the five plotted points (Fig. 8) and only Th^{227} falls outside. In case of Th^{232} isotope the α-energy is not consistent for different works. The modified Geiger-Nuttall curve gives us the clue regarding the correctness of the values of E_α. As observed from this curve, in case of Th^{232}, the value of Schintlmeister (1937) appear more satisfactory than the other.

(91) *Protoactinium*

Of six known isotopes of Pa, three are α-active. The data are given in Table IX.

Pa^{227} : This is the starting member of the co-lateral chain of Ac series. The K-capture activity is in agreement with β-energetic studies.

Pa^{228} : This is the starting member of the colateral chain of Th series. This shows high-K-capture activity as expected from β-energetics.

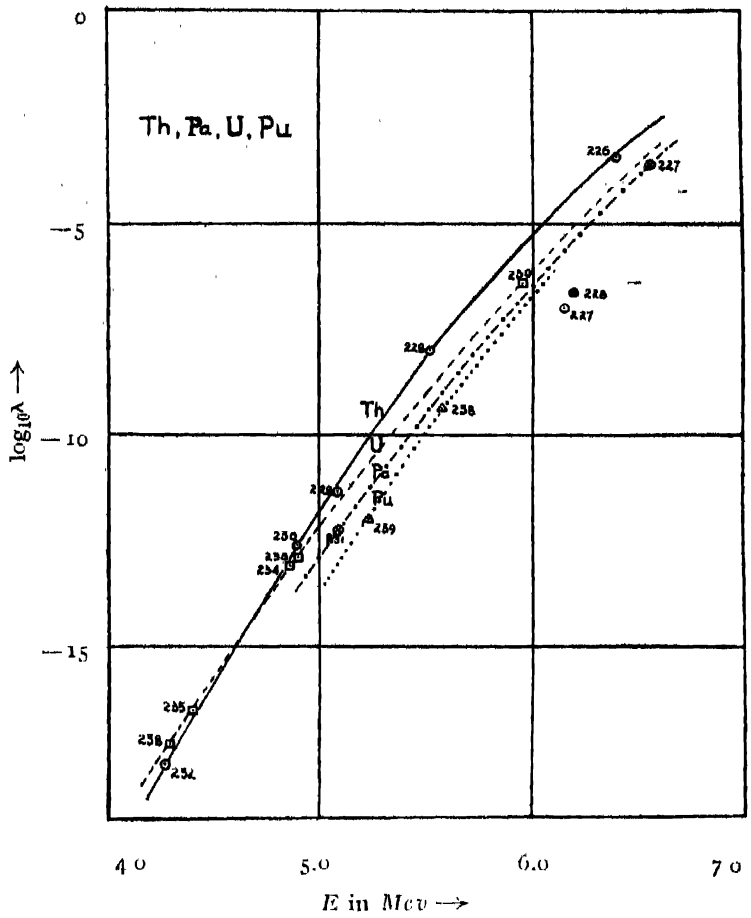

FIG. 8

Pa^{229} : Not yet known. According to β-energetics, this will decay by K-capture.

Pa^{230} : The β-activity of this follows from β^--energetics studies.

Pa^{231} : The α-particles from this isotope, so long known to be homogeneous have recently been shown to have fine structure by San-Tsiang et al (1946). Three groups of α-particles of energies 5.00, 4.72 and 4.69 MeV are found ; the intensity of group o α-particles is about 81%. Thus $\lambda_{\alpha 0}$ becomes 5.59×10^{-13} sec^{-1}.

Pa^{232} : Not yet known. May be obtained from Pa^{231} (n,γ), reaction. This isotope will show predominant β^--activity.

Pa^{233} : The observed β^--activity is in good agreement with β-energetics studies.

Pa^{234} (UX_2, UZ) : Two isomeric nuclei exists for Pa^{234}. $_{90}UX_1^{234}$ goes over to UX_2^{234} by β^--decay. UX_2^{234} has an isomeric transition to UZ^{234} and both UX_2 and UZ, decay to UII^{234} by β^--emission.

TABLE IX

Protoactinium (91)

Isotopes	Observed half-life	$\frac{\alpha}{\beta}$ ratio	α-half-life	λ_α (Sec^{-1})	β-energy (MeV)	Decay energy E (MeV)	Produced by	Remarks
Pa^{227}	38m (G2a)	$\frac{\alpha}{K} \sim \frac{5}{1}$	45.6m	2.53×10^{-4}	6.46 (G2a)	6.57	Th^{232}(d 7n)	
Pa^{228}	22h (G2a)	$\frac{\alpha}{K} \sim \frac{1}{50}$	46 8d	1.68×10^{-7}	6.09 (G2a)	6.20	Th^{232}(d,6n)	
Pa^{229}	?		...	...	...	...		This will show K-capture
Pa^{230}	17d($\tilde{\beta}$) (S12)	..	...	...	...	...	Th^{232}(d,4n) Th^{232}(α,p5n)	
Pa^{231}	3.2×10^4y (G3)	..	3.2×10^4y	6.9×10^{-13} $\lambda_{\alpha\,0}=5.6\times10^{-13}$	5.0 (S3)	5.09	$UY^{231}\beta^-$-decay	
Pa^{232}	?	...	...	...	...	...	...	This will decay by β-activity.
Pa^{233}	27.4d($\tilde{\beta}$) (G4)	..	..	...	...	...	$Th^{233}\beta^-$decay	
Pa^{234}	6.7h ($\tilde{\beta}$)	..	...	..	...	...	UX_2I.T.	
(UZ, UX_2)	1.14m($\tilde{\beta}$) I.T.	...	.	...	...	...	$UX_1\beta^-$-decay	

Geiger-Nuttall Curve for Pa.

Of three isotopes, Pa^{228} lies a little below the G-N curve for Pa (Fig. 8). This is probably due to the approximate value of $\alpha : K$ ratio.

(92) *Uranium*

At present seven isotopes of U are known. Four of these are α-active. The relevant data are given in Table X.

U^{238} : This is β-stable as expected.

U^{232} : Not yet known. Expected to show α-activity.

U^{233} : This recently discovered isotope of U is highly fissionable and this is the starting isotopes in the $(4n+1)$ radioactive series.

U^{234} : The experimental data for α-energy vary for different investigators by different methods. Latest determination of α-energy by range measurement in ionisation chamber by Wytzes and Van de Maas (1947) yield α-energy as 4.78 MeV.

TABLE X

Uranium (92)

Isotopes	Observed half life	$\frac{\alpha}{\beta}$ ratio	α-half life	λ_α (Sec^{-1})	α energy (MeV)	Decay energy E_t(MeV)	Produced by	Remarks
U^{230}	20.8d (S12)	...	20.8d	3.86×10^{-7}	5.86 (S12)	5.96	$Pa^{230}\beta^-$-decay $Th^{232}(\alpha, 6n)$	...
U^{232}	...	...	...	...	...	...	...	α-activity expected
U^{233}	1.63×10^5y (E1,H1)	...	1.63×10^5y	1.35×10^{-13}	4.825 (E1,H1)	4.898	$Th^{233}\beta^-Pa^{233}\beta^-$	
U^{234} (UII)	2.69×10^5y (N1)	...	2.70×10^5y	8.14×10^{-14}	4.71(R1) 4.78(S10) 4.76(S_5) 4.78(W_4)	4.86	$Pa^{234}\beta^-$-decay	
U^{235}	7.13×10^8y (N1)	...	7.13×10^8y	3.08×10^{-17}	4.33(V1)	4.40	Natural Source	
U^{236}	?	...	...	...	...	...	$U^{235}(n, \gamma)$?	Instantly fissioned
U^{237}	~7d(β^-) (M1, N2)	...	...	...	...	...	$U^{238}(n, 2n)$ (M1, N2)	...
U^{239}	4.56×10^9y	...	4.56×10^9y	4.82×10^{-18}	4.15(R1) 4.23(S10) 4.21(S_5) 4.21(W_4)	4.29	Natural Source	...
U^{239}	23m(β^-) (I1 S9)	...	...	...	...	...	$U^{238}(n, \gamma)$ (H14)	...

U^{235} : The α-energy is obtained from the range of α-particles and the range-energy relation of Holloway and Livingstone (1938).

U^{236} : The isotope U^{236} is not yet known. U^{235} by neutron capture becomes U^{236} which instantly undergoes fission.

U^{237} : The observed β^--activity of U^{237} is in agreement with the β-energetics studies.

U^{238} : The results of various investigations regarding α-energy of U^{238} varies to certain extent. Latest range determination by Wytzes and Van de Maas (1947) yield α-energy as 4.21 MeV. The α-particles are of homogenous energy.

U^{239} : The observed β^--activity of U^{239} is in accordance with the energetics studies. The β^- energy has not yet been measured.

The Geiger-Nuttall Curve for U.

With the data given in Table X, the log λ, E curve for the isotopes of U is drawn (Fig. 7). It is seen that all of five U isotopes lie on a smooth G-N curve for U.

(93) *Neptunium*

Np^{237} is the only α-active isotope of Np known so far, The value of α-energy is not yet known.

(94) *Plutonium*

Three isotope of plutonium are known two of which Pu^{34} and Pu^{239} are α-active. The data are given in Table XI.

TABLE XI

Plutonium (94)

Isotopes	Observed half life	$\frac{\alpha}{\beta}$ ratio	α half-life	λ_α (Sec^{-1})	α-energy, (MeV)	Decay energy E_t(MeV)	Produced by	Remark
Pu^{236}	...	...	...	..	...	...	$Np^{236}\beta$-decay $Cm^{240}\alpha$-decay	...
Pu^{238}	50y (S8)	...	50y	1.39×10^{-10}	5.49 (C1)	5.58	$Np^{238}\beta$-decay $Cm^{242}\alpha$-decay	...
Pu^{239}	24,000y (S8)	...	24,000y	9.16×10^{-13}	5.15	5.23	$U^{239}\beta$-decay	...
Pu^{241}	long(β)	..	...	...	..	...	$U^{238}(\alpha,n)$ (S8)	...

Pu^{236} : Nothing is reported about this isotope which must have been produced in β^--decay of Np^{236} and α-decay of Cm^{240}.

This will be γ-active, decaying to U^{232}.

Pu^{238} : The recent report of the range of α-particles from Pu^{238} by Chamberlain et al (1947) yield α-energy of 5.49 MeV from the range-energy curve (Holloway and Livingstone, 1938).

Pu^{239} : The range measurements by Chamberlain et al (1947) yield α-energy as 5.15 MeV.

Pu^{241} : The observed longlife β^--activity of Pu^{241} is in agreement with β-energetices studies.

The Geiger-Nuttall Curve for Pu.

With two points corresponding to two α-active isotopes of Pu, the long λ, E curve is an approximate one. The curve is of the same nature as with other elements (Fig.8).

CONCLUSION

Thus it is seen that experimental data of all α-active nuclei can be plotted quite satisfactorily on seperate Geiger-Nuttall curves for each element. Deviation occuring in some cases are mostly due to the uncertainties in the experimental data as pointed out. These curves will be of much help in ascertaining for any new α-active isotope the half life or α-energy when any one of them is known.

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