The cooperation of Mr. J. T. Vale, Mr. B. Rossi, and the crews of the 184-inch and 60-inch cyclotrons is gratefully acknowledged.

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* This paper is based on work performed under the auspices of the Atomic Energy Commission.

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Three Additional Collateral Alpha-Decay Chains

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CONTINUATION of investigations of the type which led to the observation of artificial radioactive chains collateral to the natural thorium and actinium families[1] have led to the identification of an additional collateral chain and partial identification of two others. In each case, after irradiation of thorium in the Berkeley 184-inch cyclotron the target was dissolved, and the first element in the series was isolated in an essentially weightless fraction. As before,[1] the decay and energy of the alpha-particles were measured with standard alpha-particle counting devices and an alpha-particle pulse analyzer[2] equipped with a fast sample-changing mechanism and identification of members of one of the series (the first to be mentioned) was aided by successive recoil collections.

Table I. Measured half-lives and energies.

Isotope	Type of radiation	Half-life	Energy of radiation (Mev)
${}_{92}U^{229}$	α	58 ± 3 min.	6.42
${}_{90}Th^{225}$	α	7.8 ± 0.3 min.	6.57
${}_{88}Ra^{221}$	α	31 ± 1.5 sec.	6.71
${}_{86}Em^{217}$	α	$\sim10^{-3}$ sec.	7.74
${}_{84}Po^{213}$	α	4.2×10^{-6} sec.	8.34
${}_{82}Pb^{209}$	β^-	3.32 hr.	0.70
${}_{83}Bi^{209}$	Stable		
${}_{92}U^{228}$	α	9.3 ± 0.5 min.	6.72
${}_{90}Th^{224}$	α	(~1 sec., predicted)	7.20
${}_{88}Ra^{220}$	α	($\sim10^{-2}$ sec., predicted)	7.49
${}_{86}Em^{216}$	α	($\sim10^{-5}$ sec., predicted)	8.07
${}_{84}Po^{212}(ThC')$	α	3×10^{-7} sec.	8.78
${}_{82}Pb^{208}$	Stable		
${}_{91}Pa^{226}$	α	1.70 ± 0.15 min.	6.81
${}_{89}Ac^{222}$	α	(~10 sec., predicted)	6.96
${}_{87}Fr^{218}$	α	($\sim10^{-2}$ sec., predicted)	7.85
${}_{85}At^{214}$	α	($\sim10^{-6}$ sec., predicted)	8.78
${}_{83}Bi^{210}(RaE)$	β^-	5.0 days	1.17
${}_{84}Po^{210}$	α	140 days	5.30
${}_{82}Pb^{206}$	Stable		
${}_{91}Pa^{228}$	α	22 ± 1 hr.	6.09
${}_{89}Ac^{224}$	α	2.9 ± 0.2 hr.	6.17
${}_{87}Fr^{220}$	α	27.5 ± 1.5 sec.	6.69
${}_{85}At^{216}$	α	$\sim3\times10^{-4}$ sec.	7.79
${}_{83}Bi^{212}(ThC)$	$\alpha(34\%)$	60.5 min.	6.05
	$\beta^-(66\%)$		2.20
${}_{81}Tl^{208}(ThC'')$	β^-	3.1 min.	1.82
${}_{84}Po^{212}(ThC')$	α	3×10^{-7} sec.	8.78
${}_{82}Pb^{208}$	Stable		
${}_{91}Pa^{227}$	α	38 ± 1 min.	6.46
${}_{89}Ac^{223}$	α	2.2 ± 0.1 min.	6.64
${}_{87}Fr^{219}$	α	~0.02 sec.	7.30
${}_{85}At^{215}$	α	$\sim10^{-4}$ sec.	8.00
${}_{83}Bi^{211}(AcC)$	$\alpha(99.7\%)$	2.16 min.	6.62
	$\beta^-(0.3\%)$		
${}_{81}Tl^{207}(AcC'')$	β^-	4.76 min.	1.47
${}_{82}Pb^{207}$	Stable		

The irradiation of thorium with 100-Mev helium ions resulted in the observation of the following collateral branch of the artificial $4n+1$, neptunium, radioactive family[3-5] shown with Po^{213} and its decay products:

$$
{}_{92}U^{229}\xrightarrow{\alpha}{}_{90}Th^{225}\xrightarrow{\alpha}{}_{88}Ra^{221}\xrightarrow{\alpha}{}_{86}Em^{217}\xrightarrow{\alpha}{}_{84}Po^{213}\xrightarrow{\alpha}
$$
$$
{}_{82}Pb^{209}\xrightarrow{\beta^-}{}_{83}Bi^{209}\text{ (stable).}
$$

The mass type was identified by observation of the characteristic energy of the Po^{213} alpha-particles as well as the growth of 1.5-day Pa^{229} as the electron-capture branching decay product of U^{229} (ratio $K/\alpha=\sim5$) and the growth of 10.0-day Ac^{225} as the electron-capture decay product of Th^{225} (ratio $K/\alpha=\sim0.1$). The measured half-lives and energies for the members of this series are summarized in Table I.

Immediately after 120-Mev helium ion bombardment of thorium the uranium fraction contains another series of five alpha-emitters, which is apparently a collateral branch of the $4n$ family:

$$
{}_{92}U^{228}\xrightarrow{\alpha}{}_{90}Th^{224}\xrightarrow{\alpha}{}_{88}Ra^{220}\xrightarrow{\alpha}{}_{86}Em^{216}\xrightarrow{\alpha}
$$
$$
{}_{84}Po^{212}(ThC')\xrightarrow{\alpha}{}_{82}Pb^{208}\text{ (stable).}
$$

The 9.3-minute half-life of U^{228} controls the decay rate of the series, with the half-lives of all the other members too short for them to be isolated and separately studied in our experiments. The mass type was identified by observation of the characteristic energy of the $Po^{212}(ThC')$ alpha-particles and the growth of 22-hour Pa^{228} as an electron-capture branching decay product of U^{228} (ratio $K/\alpha=\sim0.25$).

Similarly the protactinium fraction of 150-Mev deuteron-bombarded thorium shows a series of alpha-particle emitters whose rate of decay is controlled by the 1.7-minute half-life of the parent with the subsequent members all too short-lived to be isolated and separately studied. Although the mass type has not yet been identified through known daughters as above, general considerations with regard to the method of formation and half-life of the parent substance, and the energies of all the members of the series suggest a collateral branch of the $4n+2$ family:

$$
{}_{91}Pa^{226}\xrightarrow{\alpha}{}_{89}Ac^{222}\xrightarrow{\alpha}{}_{87}Fr^{218}\xrightarrow{\alpha}{}_{85}At^{214}\xrightarrow{\alpha}{}_{83}Bi^{210}(RaE).
$$

The measured alpha-particle energies of the individual members of the U^{228} and Pa^{226} series, assigned according to alpha-decay systematics in this region,[6] are shown in Table I. Also included for those members where the half-lives have not been measured are values predicted according to recent correlations between alpha-particle energies and corresponding half-lives.[7] Table I also contains our latest half-lives and energies for the members of the previously reported[1] Pa^{227} and Pa^{228} collateral chains. The radioactive properties of ThC, RaE, AcC, Po^{213}, and daughters are the accepted values taken from the literature.[8]

The cooperation of Professor R. L. Thornton, Mr. J. T. Vale, and the 184-inch cyclotron group is gratefully acknowledged. This paper is based on work performed under the auspices of the Atomic Energy Commission.

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Correction and Addendum: Scattering of Particles by the Gas in a Synchrotron*

[Phys. Rev. **74**, 140 (1948)]

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CORRECTION: The formula for P in the title of Fig. 1 should read like the right side of Eq. (18).

For the word "half" in the title of Table I, read "10 percent of."

For b in the second-last line of page 143, read B.

For $-A$ in Eq. (18) read 0.

For $\frac{1}{2}\pi$ at the end of the fourth-last paragraph of the article, read $1/2\pi$.

More accurate calculations show that for a 10 percent loss of particles, $\eta = 0.0855$ rather than 0.089.

Addendum: This note considers the effect of an initial betatron oscillation on the probability of surviving scattering of a particle being accelerated in a synchrotron or betatron. Let β be the amplitude of this initial oscillation. With appropriate choice of $t=0$, this oscillation contributes to both sine and cosine oscillations the amplitude $\beta/2^{\frac{1}{2}}$. Thus, $(1/2)\beta^2$ should be added to the right sides of Eqs. (7) and (8), and $(1/2)\beta^2(T_i/T_f)^{\frac{1}{2}}$ to the right side of (10). The maximum value of $\eta = \langle b^2\rangle/2A^2$ now occurs when

$$T/T_1 = 4/(1+\beta^2/2A^2\eta_0)^2,$$

in which η_0 is the maximum value η would have if $\beta=0$; it is

$$\eta = (\eta_0+\beta^2/16A^2)^2/\eta_0$$
$$\approx \eta_0+\beta^2/8A^2$$

for small β/A.

For example, for 10 percent loss, $\eta_0 = 0.086$. If $\beta = 2.5$ cm and $A = 8$ cm, then $\eta = 0.0982$. The higher loss can be read from Fig. 1—14.5 percent—or compensated for by a reduction in pressure of $\beta^2/8A^2\eta_0 = 14$ percent.

This calculation underestimates the loss by tacitly assuming not that the initial amplitude is β, but that the initial amplitudes obey a Rayleigh distribution with β the r.m.s. initial amplitude. It overstimates the loss by including that (small) loss which would have occurred while the amplitude of betatron oscillation was building up to initial value.

Another approach eliminates both of these errors but is unable to take account of the damping of the initial oscillation, thus overestimating the loss. This is to use the solution of (17) satisfying the boundary condition

$$p(0, B) = \delta(B-\beta) \text{ for } 0 \leq B \leq A$$

rather than $\delta(B)$. This solution is

$$p = (2B/A^2) \sum_{s=1}^{\infty} J_0(\lambda_s\beta/A)[J_1(\lambda_s)]^{-2} \times J_0(\lambda_s B/A) \exp(-\lambda_s^2\xi/A^2),$$

whence

$$P(\xi) = \int_0^A p\,dB = 2 \sum_{s=1}^{\infty} J_0(\lambda_s\beta/A) \exp(-\lambda_s^2\xi/A^2)/\lambda_s J_1(\lambda_s),$$

with $\xi = (1/2)\langle b^2\rangle$.

For $\eta = \xi/A^2 = 0.086$, $\beta/A = 0.3125$, as before, this gives $P = 18.9$ percent. For $\eta_0 \geq 0.3$, only one term of this series is significant, and it is seen that the number of protons surviving with $\beta=\beta$ is $J_0(\lambda_1\beta/A)$ times the number with $\beta=0$ ($\lambda_1 = 2.4048$, the first root of J_0); for $B/A = 0.3125$ this ratio is 86.4 percent.

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The Beta-Ray Spectra of Cu^{64}

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RADIOACTIVE Cu decays either by positron- or negatron-emission to Ni or Zn with a half-life of 12.8 hours. In 1945 Backus[1] reported disagreement between the observed ratio of the number of positrons to the number of

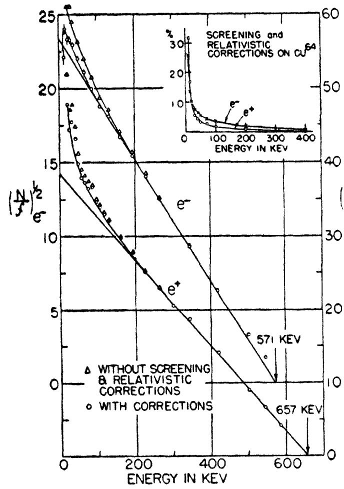

FIG. 1. Fermi plots of Cu^{64} negatron and positron spectra.