

which holds by virtue of (5), we have

$$\frac{d\delta}{dk} = 2 \int_0^R [A^{-2}u^2 - \sin^2(kr + \delta)] dr + (1/2k) \sin 2\delta. \quad (8)$$

By making  $R$  tend to infinity, and some simple substitutions

$$2 \frac{d}{dk^2} (k \cot \delta) = -2 \csc^2 \delta \int_0^\infty [A^{-2}u^2 - \sin^2(kr + \delta)] dr. \quad (9)$$

According to (1)  $r_e$  is equal to (9) taken for  $k=0$ . For small  $k$

$$\sin(kr + \delta) \sim \sin \delta (1 + kr \cot \delta) = \sin \delta [1 - (r/a)].$$

Choosing

$$A = \csc \delta, \quad (10)$$

we have finally

$$r_e = -2 \int_0^\infty \{u^2(r) - [1 - (r/a)]^2\} dr. \quad (11)$$

Here  $u(r)$  is the zero-energy wave function, normalized according to (3) and (10) in such a way that the integrand of (11) vanishes at large distances.

<sup>1</sup> J. M. Blatt, Phys. Rev. **74**, 92 (1948), Eq. (1).

<sup>2</sup> H. A. Bethe and R. Peierls, Proc. Roy. Soc. **A149**, 176 (1935), Eq. (7).

### Mass Spectrographic Assignment of Rubidium Isotopes\*

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WE have used a mass spectrograph to investigate rubidium isotopes produced by bombardment of bromine (ammonium bromide) with helium ions in the Berkeley 60-inch and 184-inch cyclotrons. The 60° deflection spectrograph is similar to that of Lewis and Hayden<sup>1</sup> but with larger dimensions and all-metal construction.<sup>2</sup>

In each bombardment with 20- to 100-Mev helium ions there was a good yield of rubidium activity with half-life about 6 hours. The rubidium activities were separated from the target material using 20–30 micrograms of inactive rubidium carrier and divided into two portions. One part was further purified and used for decay and absorption measurements. The other major portion was placed on the tungsten filament of the mass spectrograph as the nitrate or chloride. The  $Rb^+$  ions produced by heating this filament were analyzed by the instrument and caught on a photographic plate. The mass scale was fixed by the lines of natural  $Rb^{85}$  and  $Rb^{87}$ . Lines at masses 81 and 82 were shown to be radioactive both by the photographic transfer technique (Fig. 1), and by counting with a Geiger counter provided with a narrow slit. The radioactivity of natural  $Rb^{87}$  is far too weak to interfere with these experiments. With 80-Mev helium ions, 5.0-hour  $Rb^{81}$  predominated in the mixture, and with 20-Mev helium ions almost pure 6.3-hour  $Rb^{82}$  was obtained. Otherwise, the similar half-lives would have made characterization of the radiations, which are listed in Table I, very difficult. The signs of the particles were determined with a crude 180° deflection beta-spectrograph. The

TABLE I. Radiations from rubidium isotopes.

| Isotope   | Half-life | Radiations  | Produced by                          |
|-----------|-----------|---|--------------------------------------|
| $Rb^{81}$ | 5.0 hours | $\beta^+$ 0.9 Mev (abs. Al)<br>$e^-$ 0.2 Mev (spect.)<br>$\gamma$ 0.8 Mev (abs. Pb)<br>K x-rays (abs. Al, Be) | Br- $\alpha$ -2n<br>Br- $\alpha$ -4n |
| $Rb^{82}$ | 6.3 hours | $\beta^+$ 0.9 Mev (abs. Al)<br>$\gamma$ 1.0 Mev (abs. Pb)<br>K x-rays (abs. Al, Be)                           | Br- $\alpha$ -n<br>Br- $\alpha$ -3n  |

energies listed in Table I were obtained with this instrument or from absorption measurements with aluminum, beryllium, or lead, as indicated.

There are approximately equal numbers of positrons and conversion electrons from  $Rb^{81}$ . There are several x-rays and gamma-rays per positron, so that the decay is 60 to 80 percent by electron capture. The possibility of a short-lived krypton daughter complicates the interpretation of these radiations. For  $Rb^{82}$  the positron to conversion electron ratio is probably greater than five. Again, there are more x-rays and gamma-rays than positrons, corresponding to 80 to 90 percent electron capture.

The previously reported<sup>3</sup> 6.5-hour rubidium activity assigned to  $Rb^{84}$  was presumably  $Rb^{82}$ , or a mixture of  $Rb^{82}$  and  $Rb^{81}$ . No description of the radiations was reported.

Attempts to observe a krypton daughter of  $Rb^{81}$  have shown no positive results. This fact is consistent with the recent assignment of the 34-hour krypton ( $Kr^{79}$  or  $Kr^{81}$ )<sup>4</sup> activity to  $Kr^{79}$  by Woodward, McCown, and Pool.<sup>5</sup> Our experiments were not very sensitive for radiations as weak as those reported for the 13-second and 55-second krypton activities,<sup>4</sup> and we can make no statement concerning them as daughters of  $Rb^{81}$ .

Experiments are under way to characterize some longer-lived activity due to  $Rb^{83}$  and  $Rb^{84}$  produced in these same bombardments. Barber<sup>6</sup> has reported a 40-day positron emitter which he attributed to  $Rb^{84}$ .

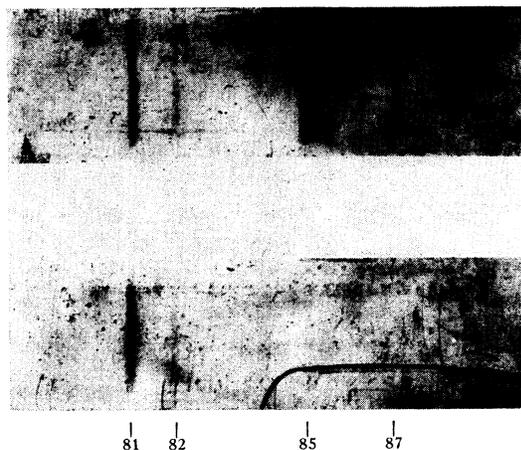


FIG. 1. The original plate shows natural  $Rb^{85}$  and  $Rb^{87}$  and radioactive  $Rb^{81}$  and  $Rb^{82}$ . The "transfer" plate is placed emulsion-to-emulsion with the original for several hours before either is developed, to locate radioactive material.

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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<sup>1</sup> L. G. Lewis and R. J. Hayden, U. S. Atomic Energy Commission Report MDDC 1556, *A Mass Spectrograph for Radioactive Isotopes* (1947); R. J. Hayden, *Phys. Rev.* **74**, 650 (1948).

<sup>2</sup> We are greatly indebted to Dr. A. J. Dempster, Dr. M. G. Inghram, and Dr. R. J. Hayden for information and advice concerning their techniques and the design of this instrument.

<sup>3</sup> J. O. Hancock and J. C. Butler, *Phys. Rev.* **57**, 1088 (1940).

<sup>4</sup> G. T. Seaborg, *Rev. Mod. Phys.* **16**, 1 (1944).

<sup>5</sup> L. L. Woodward, D. A. McCown, and M. L. Pool, *Phys. Rev.* **74**, 761 (1948).

<sup>6</sup> W. C. Barber, *Phys. Rev.* **72**, 1156 (1947).

### Three Additional Collateral Alpha-Decay Chains

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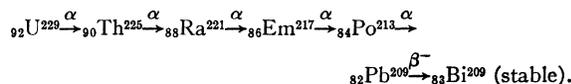
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CONTINUATION of investigations of the type which led to the observation of artificial radioactive chains collateral to the natural thorium and actinium families<sup>1</sup> have led to the identification of an additional collateral chain and partial 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

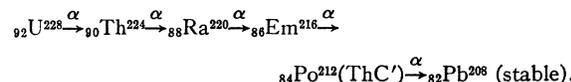
the series was isolated in an essentially weightless fraction. As before,<sup>1</sup> the decay and energy of the alpha-particles were measured with standard alpha-particle counting devices and an alpha-particle pulse analyzer<sup>2</sup> equipped with a fast sample-changing mechanism and identification of members of one of the series (the first to be mentioned) was aided by successive recoil collections.

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<sup>3-5</sup> shown with Po<sup>213</sup> and its decay products:



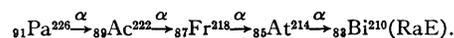
The mass type was identified by observation of the characteristic energy of the Po<sup>213</sup> alpha-particles as well as the growth of 1.5-day Pa<sup>229</sup> as the electron-capture branching decay product of U<sup>229</sup> (ratio  $K/\alpha \approx 5$ ) and the growth of 10.0-day Ac<sup>225</sup> as the electron-capture decay product of Th<sup>225</sup> (ratio  $K/\alpha \approx 0.1$ ). 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:



The 9.3-minute half-life of U<sup>228</sup> 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<sup>212</sup>(ThC') alpha-particles and the growth of 22-hour Pa<sup>228</sup> as an electron-capture branching decay product of U<sup>228</sup> (ratio  $K/\alpha \approx 0.25$ ).

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:



The measured alpha-particle energies of the individual members of the U<sup>228</sup> and Pa<sup>226</sup> series, assigned according to alpha-decay systematics in this region,<sup>6</sup> 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.<sup>7</sup> Table I also contains

TABLE I. Measured half-lives and energies.

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

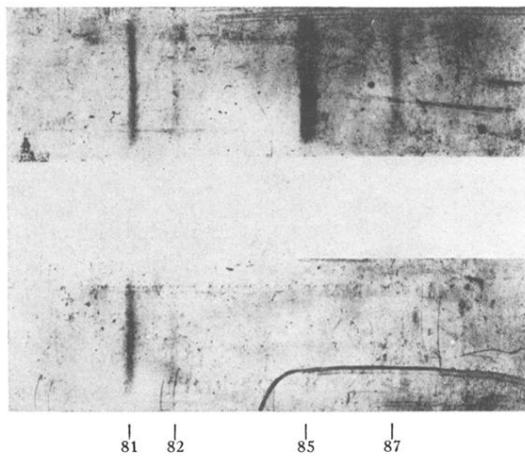


FIG. 1. The original plate shows natural  $\text{Rb}^{85}$  and  $\text{Rb}^{87}$  and radioactive  $\text{Rb}^{81}$  and  $\text{Rb}^{82}$ . The "transfer" plate is placed emulsion-to-emulsion with the original for several hours before either is developed, to locate radioactive material.