Radioactive Isotopes of Sr, Y and Zr

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Radioactive isotopes formed by bombardment of Rb, Sr and Y by protons, deuterons and neutrons are reported. The following are the periods and assignments: 2.75-hr. (Sr*++, e-, γ); 70-min. (Sr*, e-, γ); 66-day (Sr*, K, γ); 80-hr. (Y**, K); 14-hr. (Y**, e-, γ); 105-day (Y**, K, γ); 4.5-min. (Zr*++, γ); 78-hr. (Zr*, β*). (In each case e- means conversion electrons, not nuclear β-rays.) The electron spectrum of the 2.75-hr. Sr** shows a single line at 360 kev and this period is shown to grow from the 80-hr. Y**, but not from the 14-hr. isomer.

The bombardment of Rb, Sr and Y targets by 6.7-Mev protons, 4.5-Mev deuterons and slow and fast neutrons produces at least twelve radioactive periods. We have studied ten of these, many of which have also been studied by Stewart, Lawson and Cork⁴ and by Stewart. These results show several periods not reported by them and an important change of assignment of one Sr period. The stable isotopes of Sr, Y and Zr together with the probable assignments of the radioactive periods are shown in Fig. 1.⁴

The targets were usually in the form of chloride salts or in the case of Sr, the pure element. SrCl₂ could also be satisfactorily bombarded when fused onto a stainless steel plate contained in an evacuated cup attached to the exit window of the cyclotron. Beam currents to the cup were usually of the order of 1 or 2 µa of protons or deuterons. In some cases targets were bombarded on an internal probe where the beam current is about 20 µa. Activities were followed with a Frenon-filled ionization chamber and d.c. amplifier. A magnetic cloud chamber and a β-ray spectrograph were used to study β-ray and γ-ray spectra while a Geiger-Müller counter with a scale-of-eight was sometimes used for absorption measurements.

To separate Sr chemically from Rb the RbCl was dissolved in water and Na₂CO₃ was added in excess. There was no attempt made to recover the rubidium. Yttrium was separated from Sr either as the hydroxide by the addition of NH₄OH or, in the later experiments, with 8-hydroxyquinoline (oxine) by using a technique originally developed for the separation of Al from alkaline earths.⁵ The method is as follows: 0.17 g of oxine is dissolved in 12.5 cm³ of acetone and the solution is diluted to about 50 cm³ with water. About 5 mg of YCl₃ is added as a carrier to the bombarded Sr which is dissolved in 15 cm³ of water. 7.5 cm³ of the oxine solution is added to this solution and NH₄OH is added by drops until the ammonia odor is noticeable. This solution is warmed on a water bath to coagulate the precipitate and is filtered out in a Gooch crucible containing filter paper. This method has the advantage that it gives more nearly complete separations than the hydroxide method and also gives a crystalline precipitate which is more readily filterable.

Zirconium was separated from bombarded Y as the iodate in nitric acid solution, with a trace of Zr(NO₃)₄ added as carrier.

In all cases the filtered precipitate was left on a disk of filter paper 2 cm in diameter and

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4. Our results, together with other unpublished data from this laboratory, were transmitted to Dr. G. T. Seaborg for inclusion in the table by J. L. Livingood and G. T. Seaborg, Rev. Mod. Phys. 12, 30 (1940).

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Fig. 1. Stable isotopes with relative abundance and probable assignment of radioactive periods.
held in place with Scotch tape, which provided a convenient form for the measurement of radioactivity.

1. **Radioactive Isotopes of Sr**

Bombardment of Rb by protons produces a strong activity in the Sr fraction whose decay curve is shown in Fig. 2. The chief component is a period of 2.75 ± 0.1 hr. If the bombarded Rb sample is covered with a Be plate 2 mm thick the 2.75-hr. period is greatly reduced in intensity while a period of 70 minutes and one of 66 days becomes evident (see lower curve). The 70-min. period is almost completely masked without the Be absorber. This Be plate has an absorbing power equal to about 90 mls of Al for β-rays but has negligible absorption for x-rays and γ-rays. Apparently therefore very few charged particles are associated with these 70-min. and 66-day periods, the radiation consisting largely of x-rays and γ-rays. The 2.75-hr. activity consists largely of negative electrons.

There are only two stable isotopes of Rb, of masses 85 and 87, the latter being naturally β-active with a period of 10⁹ years. Rb(ρ, n) reactions therefore would yield only Sr⁸⁸ and Sr⁸⁷. Since Sr⁸⁷ is stable it would appear necessary at first sight to assign all three periods to Sr⁸⁸. However it will be shown below that the 2.75-hr. period must be assigned to a metastable state of Sr⁸⁷. The 70-min. and 66-day periods are therefore assigned to Sr⁸⁸. Since Rb⁸⁴ does not exist and Sr⁸⁸ is very rare these Sr⁸⁸ periods are not produced in observable amounts by deuteron or neutron bombardment of Rb or Sr.

**Sr⁸⁵ (70 min. and 66 day)**

As shown in Fig. 2 the activity of these two periods is only slightly reduced by covering the sample with Be. Since no positrons can be observed and since Y⁸⁷ is not stable it is concluded that this isotope decays by K capture to Rb⁸⁵. The γ-ray spectrum of the short period can not easily be obtained because of the presence of the strong 2.75-hr. period. However in β-ray spectrograph plates taken to get the electron spectrum of this latter period, a faint electron line is observed at 160 kev. (Fig. 3.) Since this line does not appear when the 2.75-hr. period is formed in other ways it can probably be associated with the 70-min. Sr⁸⁵. It seems probable then that the 70-min. isomer decays to the 66-day isomer with the emission of a partly converted γ-ray of about 170 kev (the K-ionization energy for Sr being about 10 kev).

The decay of the 66-day isomer by K capture to Rb⁸⁵ is accompanied by a γ-ray whose absorption coefficient in lead indicates an energy of about 0.8 Mev.

**Sr⁸⁷ (2.75 hr.)**

As indicated in an earlier communication this period is the same as the 3.0-hr. period reported by Stewart Lawson and Cork and by Stewart. It was formed in their experiments by Sr+d and Sr+n and assigned to Sr⁸⁷, isomeric with the 55-day period. The formation of this activity by protons on Rb eliminates this possible assignment. Its formation by Sr+d and Sr+n would allow its assignment to Sr isotopes 85 (weak), and 87 as well as 89. Since Sr⁸⁷ is stable it would be natural to make the assignment to Sr⁸⁷. However it is found that the same period is also formed by Sr+p. The only way in which a Sr activity could be formed from Sr+p is either by a p−n reaction leading to a metastable state of a stable isotope, or by decay of an yttrium activity formed during the bombardment. If the latter is formed by a p−n process the decay product must also be an isomeric state of a stable nucleus thus eliminating assignment to Sr⁸⁸. As will be seen below the 2.75-hr. period does indeed grow from an 80-hr. Y activity formed both by Sr+p and Sr+d, an activity which can be independently assigned to Y⁸⁷.
This makes the assignment of the 2.75-hr. period to a metastable state of Sr$^{87}$ quite certain.

In the Sr$+n$ bombardments an activity assigned to Sr$^{87+}$ could be formed either by the $n-\gamma$ or the $n-n$ excitation process. We have mounted a pure Sr sample in a Cd box immediately behind a Be probe within the cyclotron chamber. Since it was there exposed to a high intensity of medium fast neutrons and but few slow neutrons the $n-\gamma$ process would probably be unimportant. On the other hand, the neutrons formed by Be$+p$ are not fast enough to cause an $n-2n$ process. The 2.75-hr. period was produced under these conditions with fair intensity, suggesting the $n-n$ process. By mounting an In sample of similar dimensions adjacent to the Sr sample an estimate of the relative yields of the two reactions Sr$^{87}(n,n)\text{Sr}^{87+}$ and In$^{115}(n,n)\text{In}^{115+}$ (4.1 hr.) could be made. The yield for the latter process (calculated for infinite bombardment of the pure isotope) is about 2 to 4 times as great as for the former. The actual ratio may be greater than this since the $n-\gamma$ process may contribute in the first case (Sr$^{85}$ being fairly abundant) but not in the second (since In$^{114}$ is not stable). This difference in yields may be connected with the fact that the spin of the ground state of In$^{115}$ is 9/2 and of Sr$^{87}$ is 1/2. Hence the spin of the isomeric In$^{115+}$ is probably 1/2 and of Sr$^{87+}$ probably 9/2.

The electron and $\gamma$-ray spectrum of this 2.75-hr. period is of particular interest. If it is assigned to either Sr$^{85}$ or Sr$^{87+}$ the decay must be either by positron emission or $K$ capture since the corresponding Y isotopes are not stable. The cloud-chamber measurements of Stewart et al. showed an apparently continuous spectrum of low energy negative electrons. This was indeed a strong reason for assigning the period to Sr$^{85}$ where it could decay by electron emission to stable Y$^{85}$. Our cloud-chamber histogram (C) is compared to theirs (B) in Fig. 4. For clarity the two are drawn to different scales. The high energy tracks above $H\rho$ 3300 in curve B are from the 55-day Sr$^{89}$ also present in their specimen, but not in ours. Stewart, Lawson and Cork found this histogram to fit a K–U plot.

However, when a thin specimen showing this activity is placed in the $\beta$-ray spectrograph a spectrum consisting only of a single line at $H\rho$ 2360 is obtained. Two such plates are shown in Fig. 3, one taken with a Rb$+p$ specimen and the other from Sr$+p$. Exactly similar plates were obtained from a Sr$+d$ bombardment. The microphotometer curve for one of these plates is plotted as A in Fig. 4, showing a much narrower peak than the cloud-chamber data. It is evident that for electrons of this low energy (360 kev) the scattering of the particles in the cloud-chamber gas (plus self-absorption in the specimen if thick) broadens out the histogram to such an extent as to conceal the homogeneity of the electron spectrum.

The results with the $\beta$-ray spectrograph make it certain that the observed electrons are con-

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version electrons accompanying a transition gamma-ray and are not nuclear $\beta$-rays. The final necessity of assignment of this period to Sr$^{89}$ is removed and the assignment to Sr$^{87}$ becomes unambiguous.

That Sr$^{87*}$ decays by isomeric transition to the stable state Sr$^{87}$ rather than by $K$ capture to Rb$^{87}$ is almost certain since Rb$^{87}$ is itself naturally $\beta$-active decaying to Sr$^{87}$. This latter decay must always be to the ground state of Sr$^{87}$ since the maximum $\beta$-ray energy is only 130 kev and there is no evidence in the Rb$^{87}$ spectrum of the Sr$^{87*}$ electrons. Also we have been unsuccessful in separating active Sr from natural Rb.\(^8\)

That the $x$-rays accompanying the Sr$^{87*}$ transition are Sr rather than Rb $K$ $x$-rays was shown roughly by absorption experiments in Se and Br. Thin evaporated layers of Se on Al foil and distilled layers of CBr$_4$ on Al were used as absorbers. The absorption coefficient in Br was of the same order of magnitude as in Se, whereas for Rb $K$ $x$-rays it should have been several times smaller. The measurements are only rough because the only samples of the 2.7-hr. period strong enough for these tests were those formed by Rb($\bar{p}, n$) in which the Sr$^{87}$ periods were also strong.

2. RADIOACTIVE ISOTOPES OF Y

Bombardment of Sr with protons yields four periods in Y. A 2-hr. positron emitting period

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showing that the isomeric 14-hr. period of \( ^{87}Y \) does not decay to \( ^{87}Sr \). Presumably this 14-hr. state decays to the 80-hr. state with gamma-ray emission.

Also the initial activities of the \( Y \) fractions decay along a curve which does not show any 80-hr. component, indicating that practically the entire activity of this period is assignable to the \( ^{87}Sr \) conversion electrons. When these electrons are filtered out with a Be plate there is, however, evidence for the \( Sr-K \) x-rays which accompany the \( K \)-capture decay of \( ^{87}Y \) to \( ^{87}Sr \). We have detected no 80-hr. gamma-ray, however.

The 14-hr. isomeric transition in \( ^{87}Y \) appears from absorption measurements (made immediately after separation) to be accompanied by a gamma-ray of about 500 kev and a few corresponding conversion electrons. Measurements of these are made difficult, however, by the rapid rise of the 2.7-hr. activity.

The 100-day period appears to decay by \( K \)-electron capture and the emission of a fairly high energy unconverted \( \gamma \)-ray. Absorption measurements of the \( \gamma \)-ray in Pb, Al, and Cu indicate a \( \gamma \)-ray of about 2 Mev, but absorption measurements at these energies are quite uncertain and the \( \gamma \)-ray may even be as low as 1 Mev in energy, or may be a mixture of two or more. The fact that the 100-day period is formed by protons on \( Sr \), but not by deuterons makes the most probable assignment \( ^{86}Y \).

In one of the earlier multiple separations after deuteron bombardment of \( Sr \) we found a 15±2-day period in the \( Y \) fraction. We assigned it tentatively to \( ^{88}Y \) since it was not observed as a product of proton bombardment. This separation was done by the hydroxide method. A later attempt to find this period was unsuccessful with the oxine method of separation, and hence was undoubtedly due to an impurity (\( ^{89}P \)).

3. \( Zr \) Periods

The bombardment of \( Y \) with protons produced two strong periods of 4.5 min. and 78±1 hour (see Fig. 7), which are chemically identified as \( Zr \). The 4.5-min. period appears to be associated with an isomeric transition in \( Zr^{89} \). This is shown by the cloud-chamber observation that many \( \gamma \)-rays are present while the 4.5-min. period is strong, but after this period has died out only positrons are observable. Range measurements in Al show these to have a maximum energy of about 1 Mev. There are no \( \gamma \)-rays associated with the 78-hr. period.

These two activities must be isomers of \( Zr^{89} \) because no other \( Zr \) isotope can be produced from \( Y \) by a \( p - n \) reaction.

The results reported herein are summarized in Table I. The 55-day \( Sr^{89} \) and the 2-hr. \( Y^{88} \) are omitted since though we observed them we have nothing to add to the data of Stewart.\(^3\)

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![Fig. 7. Decay of Zr from Y+H\(^+\).](image_url)
Fig. 3. (A) Electron spectrum of Sr from Rh-H³, (70 min., 2-75 hr.) (B) Spectrum of Sr bombarded with protons. (80-hr. period).