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The Excitation of Heavy Nuclei

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A new metastable isomer of gold was found. The energy level system of gold has been studied in the region from the threshold to 3.3 Mev. The energy of the metastable state was found to be approximately 250 kev and higher activation levels which combine with the metastable state are found at 1.22±0.03, 1.68, 2.15, 2.56, and 2.97 Mev, respectively. This excitation has also been produced by fast neutrons by the Au-*n*-*n* reaction and the threshold for this process has been determined. The previously known 43-minute period of mercury has been produced by direct x-ray irradiation as well as a 42-day period in columbium. The strontium activity, known previously from neutron excitation, of 2.7 hours half-life has been produced by both x-ray and electron bombardment of this element.

INTRODUCTION

ALTHOUGH activity may be produced in stable nuclei by means of the ordinary reactions such as γ-n, n-$2n$, n-γ, n-α, p-n, etc., the most direct proof of the existence of a metastable state in such stable nuclei lies in the production of this activity by the direct irradiation of the element by x-rays or electrons below the threshold for photo-disintegration of the given nucleus. At these energies the only activity which can be produced is that which is excited in one of the isotopes originally present and, therefore, can be attributed to a metastable state of a stable nucleus. If the metastable state belongs to a relatively abundant isotope, one can produce sufficient activity, even at low energies, and thus obtain an excitation curve[1] from which may be obtained much valuable information concerning the nuclear energy level system of that nucleus.[2]

The Van de Graaff-Herb electrostatic generator furnishes a convenient and suitable source of x-rays and electrons for the study of these excitation curves. In a quantitative determination of the energies of the various activation levels which combine with the metastable state, the x-ray excitation curve is the more accurate of the two. When the energy of the monokinetic electron beam, which produces the x-rays, reaches a higher activation level, the curve shows a sharp increase in slope. The intersection of the two linear portions of the curve, each obtained from numerous experimental points, clearly defines the energy of this activation level. It is not possible to produce excitation by a natural source of γ-rays since the process is one of line absorption, the natural width of the line being of the order of millivolts while the total width, including the Doppler effect, is of the order of a few volts.

EXPERIMENTAL

A. Mercury

An activity with a half-life of 43 minutes has been observed and chemically identified as mer-

[1] B. Waldman, G. B. Collins, and E. M. Stubblefeld, Phys. Rev. **A55**, 1129 (1939); M. L. Wiedenbeck, Phys. Rev. **67**, 92 (1945).
[2] E. Guth, Phys. Rev. **59**, 325 (1941).

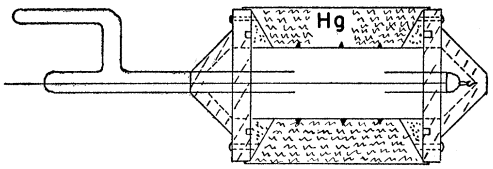

FIG. 1. Thin walled aluminum counter. The bombarded mercury was contained between the outer cylinder and the counter wall.

cury by Heyn,[3] and others[4,5] when mercury is irradiated with fast neutrons in the process Hg-n-$2n$. This activity was also produced by Krishnan and Nahum[6] by the Hg-d-p reaction. It was not clear whether this activity was to be ascribed to a metastable state of a stable mercury nucleus or to an unstable nucleus which decays to Au by K-capture.[6]

We have now produced the activity with this period by bombarding mercury with x-rays of maximum energy of 2.6 Mev. The metallic mercury was irradiated for thirty minutes with the x-rays produced when an electron beam current of 150 microamperes struck a thick gold target. The mercury was then poured around a thin walled aluminum counter (Fig. 1). The decay curve shown in Fig. 2 clearly indicates the presence of the 43-minute period which can, therefore, definitely be attributed to Hg*. The relatively small activity prohibits the obtaining of a complete excitation curve at the present time and indicates that the isotope possessing the metastable state is relatively low in abundance.

B. Strontium

The isotope Sr^{87} has been shown to possess a metastable level 0.38 Mev above the ground state. This has been excited by the Sr^{87}-n-n[7,8] reaction as well as having been grown in the processes: Rb-p-n,[9] Sr-n-γ,[8,9] Zr-n-α,[10] and from Y^{87} by K decay.[7] This 2.7-hour activity has now also been produced by the direct x-ray bombardment of strontium in the reaction: $Sr^{87}+\gamma \rightarrow Sr^{87*}$ and by the electron bombardment of strontium chloride in the reaction:

$$Sr^{87}+e_{\nu 1} \rightarrow Sr^{87*}+e_{\nu 2}.$$

C. Columbium

A radioactive isomer of stable Cb^{93} has been produced in the beta-decay of Zr^{93}.[10–13] Sagane, *et al.*[10] have reported a half-life of the order of 55 days. Pool and Edwards[13] have more recently reported a decay period of 38.7 days for this activity. After eighteen hours of bombardment with x-rays produced by a beam of 150 microamperes of 2.6-Mev electrons stopped on a gold target, a small columbium sample showed an initial activity of 2000 counts per hour when the sample was placed before a thin windowed (1.5-mil Al) counter. This activity was found to decay with a half-life of approximately 42 days.

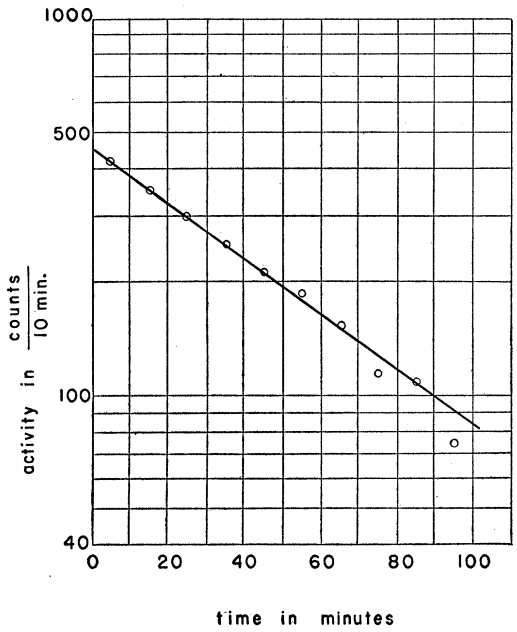

FIG. 2. Decay curve for Hg*. The half-life of mercury in the transition: Hg*→Hg+γ is 43 minutes.

[3] F. Heyn, Nature **139**, 842 (1937).
[4] E. McMillan, M. Kamen, and S. Ruben, Phys. Rev. **52**, 375 (1932).
[5] M. L. Pool, J. M. Cork, and R. L. Thornton, Phys. Rev. **52**, 239 (1937).
[6] R. S. Krishnan and E. A. Nahum, Proc. Camb. Phil. Soc. **36**, 490 (1940).
[7] L. A. Dubridge and J. Marshall, Phys. Rev. **57**, 348 (1940).
[8] H. Reddemann, Naturwiss. **28**, 110 (1940).
[9] L. A. Dubridge and J. Marshall, Phys. Rev. **56**, 706 (1939).
[10] R. Sagane, S. Kojima, G. Miyamoto, and M. Ikawa, Phys. Rev. **57**, 1180 (1940).
[11] O. Hahn and F. Strassmann, Zeits. f. Physik **121**, 729 (1943).
[12] W. N. Moquin and M. L. Pool, Phys. Rev. **65**, 60 (1944).
[13] M. L. Pool and J. E. Edwards, Phys. Rev. **67**, 60 (1945).

D. Gold

We have previously reported[14] an activity of half-life 7.5 ± 0.5 seconds which was produced by the bombardment of gold with an x-ray beam. Since there is but one stable isotope of gold, this activity must be attributed to a metastable state in Au^{197}.

In the ground state gold has a spin of 3/2 which, therefore, would imply a spin of 9/2 or 11/2 for the metastable state. Gold is the first known isotope in which the spin in the ground state is other than 1/2 or 9/2 and is thus an exception to the empirical rule set forth by Mattauch[15] that stable isotopes possessing such metastable states will have spins of 1/2 or $\geqslant 9/2$.

This activity has been determined as a function of the accelerating potential from the threshold to 3.3 Mev and is shown in Fig. 3. The activity is given as the number of counts during the first minute starting five seconds after the sample had been bombarded for thirty seconds with x-rays produced by an electron beam of 100 microamperes. The sample which was used in these measurements was a gold cylinder which formed the cathode of a self-quenching argon-ether counter. Several of such cylinders had been tried including a copper cylinder plated on the inside with $\frac{1}{2}$ mil of gold. However, a pure gold cylinder was found to be most satisfactory and was used in obtaining all measurements.

As in the previous cases, it is seen that the excitation curve is composed of a series of straight line segments, the intersection of which gives the positions of the higher activation levels which combine with the metastable state. These breaks are found at 1.22 ± 0.03 Mev, 1.68, 2.15, 2.56 and 2.97 Mev, respectively.

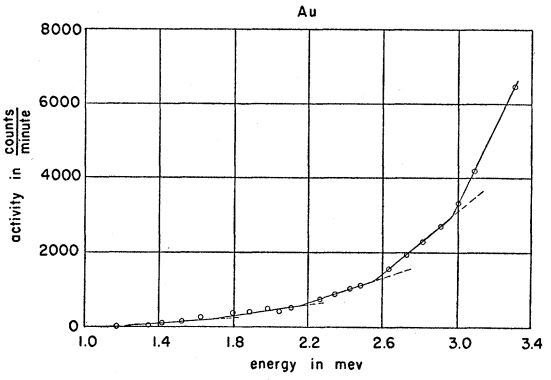

FIG. 3. X-ray excitation curve for gold. The intersection of the straight line segments gives the energy of the activated levels which combine with the metastable state.

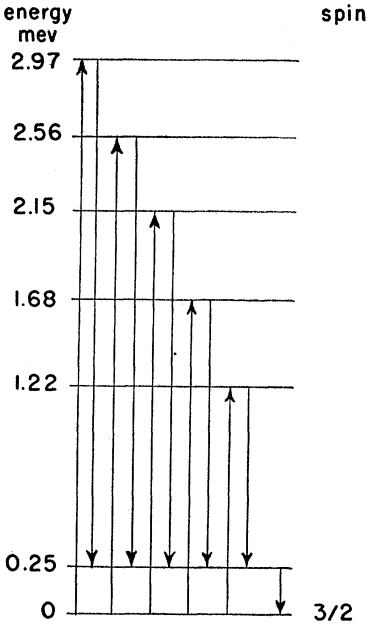

FIG. 4. Nuclear energy level diagram for gold showing the various transitions which occur.

The energy of the metastable level was obtained by measuring the energy of the conversion electrons emitted in the transition: $Au^{197*}\rightarrow Au^{197}+\gamma$. A thick gold disk was placed before the thin window of a counter with a brass cylinder, and the sample was irradiated at a fixed accelerating potential and with a constant beam current. Aluminum foils were interposed between the counter and the gold, and thus the activity was determined as a function of the thickness of aluminum. From this data, one obtains a value of approximately 250 kev for the energy of this level.

A nuclear energy level diagram showing the various levels which combine with the metastable level and the transition involved is shown in Fig. 4.

Activities due to metastable states of stable nuclei have been produced in several instances[7,16] by the inelastic collision of fast neutrons with the

[14] M. L. Wiedenbeck, Phys. Rev. **67**, 53 (1945).
[15] J. Mattauch, Zeits. f. Physik **117**, 246 (1941).
[16] M. Goldhaber, R. D. Hill, and L. Szilard, Phys. Rev. **55**, 47 (1939); Nature **142**, 521 (1938).

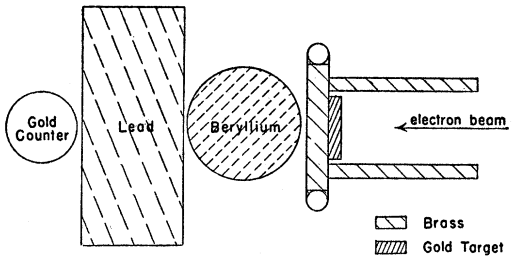

FIG. 5. Target arrangement for the excitation of gold with neutrons produced from the Be-γ-n reaction.

stable nucleus. Up to this time no quantitative data have been obtained concerning the energy of the neutrons required to produce this excitation. One should expect, of course, that the neutron threshold is practically identical with the x-ray threshold, but a direct proof is of interest. The electrostatic generator furnishes a convenient source of neutrons of known energy which can be produced by the Be-γ-n reaction. The distribution of energies of the neutrons is continuous as is the x-ray spectrum which produces them.

The intensity of any neutron line is linear[17] (in this energy region) with the applied accelerating potential above its threshold. The maximum energy of the neutrons so obtained is: $V_n=8/9(V-1.63)$, where V is the applied electron accelerating voltage.

Since the threshold for the gold excitation was found to be 1.22 Mev with x-rays, it seemed possible that this activity could also be produced with the neutron spectrum described above. Gold has the additional advantage over any other known metastable isomer since it exhibits no other short period neutron capture reactions.

An arrangement was set up as shown in Fig. 5. The x-rays were allowed to strike one-half pound of powdered beryllium placed directly in front of the target. Lead of four-inch thickness was placed between the beryllium and the self-quenching counter containing the gold cathode. The lead served as a shield to protect the counter from the x-rays.

With the apparatus set up in this manner, the activity produced by the x-rays was determined by bombardment without having the beryllium in position. Next, the beryllium was placed in position. No increase in activity beyond the small residual x-ray activity was found until the maximum energy of the neutrons exceeded 1.22 Mev. With maximum neutron energies in the range from 1.22 to 1.3 Mev, a considerable excess counting rate was obtained which increased linearly with energy as in the case of x-ray excitation. This indicates that the threshold for the process, $Au^{197}+n_{\nu 1}\rightarrow Au^{197*}+n_{\nu 2}$, is identical with that of x-rays.

DISCUSSION

Again, as in the case of silver, cadmium, and indium, the energy levels of gold were found to start in the region of 1.2 Mev, and successive higher levels are approximately equally spaced with a difference of 0.4 Mev between them. No convergence of the levels is indicated at these energies.

These experiments check the theory and show that the excitation processes in the cases of x-rays, electrons, and neutrons are similar. As one increases the energy of the x-rays or electrons producing the excitation, one eventually reaches a limit when this energy is equal to the binding energy of a neutron in the nucleus and thus produces the photo- or electro-disintegration of that nucleus. The similarity with the neutron process indicates that when the energy of the incident neutrons reaches the binding energy of a nuclear neutron, the n-$2n$ process can occur.[18] This process may be looked upon as one of neutro-disintegration, differing from that of photo-disintegration, however, due to the required momentum consideration of the incident neutron.

ACKNOWLEDGMENT

The author takes great pleasure in thanking Dr. Eugene Guth for his assistance with these problems.

[17] M. L. Wiedenbeck and Rev. C. J. Marhoefer, Phys. Rev. 67, 54 (1945).

[18] V. F. Weisskopf and D. H. Ewing, Phys. Rev. 57, 47 (1940).