Beryllium-Proton Reactions and Scattering

R. G. THOMAS, S. RUBIN, W. A. FOWLER, AND C. C. LAURITSEN
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
March 28, 1949

THE cross sections of the reactions $Be^9(p,d)Be^8$, $Be^9(p,\alpha)Li^6$, and $Be^9(p,p)Be^9$ have been measured at a laboratory angle of 138° for bombarding energies from 250 to 1300 kev using a high resolution double-focusing 180° magnetic spectrograph for reaction particle analysis.[1] Figure 1

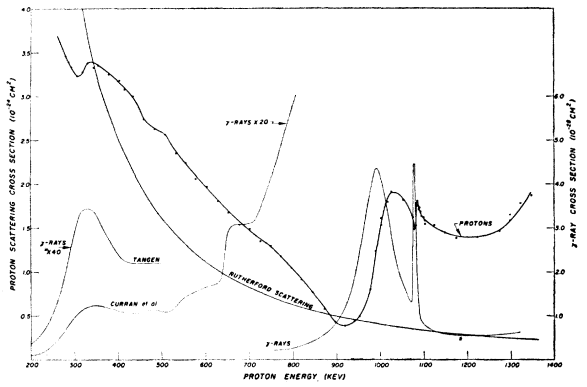

FIG. 1. Cross section for scattering of protons by beryllium at 138° (142° in center of mass coordinates). The energy scale should be increased by 0.32 percent. The cross section is 4π times the differential cross section per unit solid angle.

shows the proton scattering cross section and, for comparison, the $Be^9(p,\gamma)B^{10}$ data of Tangen,[2] Curran,[3] and Fowler, Lauritsen, and Lauritsen,[4] are included. The cross sections shown are 4π times the differential cross section per unit solid angle in center of mass coordinates. The energy scale was calibrated[2] by measurements on the strong $F^{19}(p\alpha',\gamma)$ resonance at 873.5 kev.[5] Particle detection was by means of an ionization chamber and linear amplifier. By observing the Rutherford scattering of protons from copper, it was found that counting was reliable down to 180 kev, where the pulses began to fall into the background noise. Figure 2 shows the reaction cross sections for disintegration into alpha-particles and deuterons. Below 750-kev bombarding energy, the alphas and deuterons could not be resolved magnetically since they have nearly the same curvature in the field, so it was necessary to use amplifier pulse size discrimination, a procedure which involves some error due to the straggling of the alpha-particles and deuterons in the target and chamber windows.

In measuring the alpha-particle cross section, the spectrograph field was adjusted for counting He^{++} ions; consequently, it was necessary to correct the yields for the number of He^+ ions which were not counted. Henderson,[6] Briggs,[7] and Rutherford[8] have studied the capture and loss exchange between He^+ and He^{++} in various substances. Their results

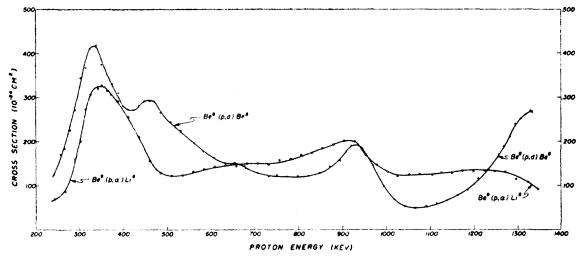

FIG. 2. Cross section for the $Be^9(pd)Be^8$ and $Be^9(p\alpha)Li^6$ reactions at 138°. The energy scale should be increased by 0.32 percent. The cross section is 4π times the differential cross section per unit solid angle.

show that although the equilibrium ratio of these two ions varies considerably with velocity, it is not a function of the substance penetrated. This is consistent with the calculations made by Bohr,[9] which indicate that the ratio of capture and loss cross sections is proportional to the inverse one-third power of the atomic number of the stopping material. Thin contamination layers of carbon and oxygen on the beryllium actually determine the ratio of the two types of ions in our case. We have used the experimental results for mica. No correction was made for the number of neutral helium atoms, as the equilibrium ratio of neutral to doubly charged alpha-particles is very small for the velocities dealt with here. No experimental data are available on the capture-and-loss ratio for protons and deuterons in the energy range with which we were concerned, so no correction was made. The analysis by Bohr indicates a ratio of neutral to singly charged protons of less than 5 percent for proton energies greater than 120 kev.

The yield of particles at each bombarding voltage was obtained by adjusting the field of the magnetic spectrograph so that only particles from a thin layer of the target somewhat below the surface were counted. The advantages of such a procedure are that surface contamination layers are avoided and that even though thick targets are employed a thin target yield curve is obtained, the target thickness in energy units being determined by the over-all resolution of the apparatus.

The over-all resolution, taking into account spectrograph resolution, size of the incident beam, spread in energy of the incident particles, straggling in the target, and change in energy of the scattered particles with angle of scattering, corresponded to a small effective spread in incident particle energy. This appreciably affected only the shape of proton interference at the narrow resonance at 1087 kev. At this energy the resolution was such that for a fixed bombarding energy and spectrograph setting protons were accepted by the spectrograph whose energy before scattering had a spread of 1 kev. From γ-ray studies[4] this resonance is found to have a natural width of 3–4 kev. The cross section is proportional to the yield multiplied by the stopping cross section of the target atoms.

The proportionality factor involves the ratio of the solid angle of the entrance window of the spectrograph to the energy interval accepted at the exit window. This was obtained by measuring the yield of protons scattered by copper and assuming the Rutherford formula for the cross section to hold. The stopping cross section for copper as a function of proton energy was obtained from the data of Mano,[10] while that for beryllium was obtained from the recent measurements by Madsen and Venkateswarlu.[11]

The proton scattering cross section shows prominent anomalies near 998 and 1087 kev, where marked resonance occurs in the cross section for the $Be^9(p\gamma)B^{10}$ reaction. Interference effects predicted for elastic scattering by the Breit-Wigner formula are indicated. Deviations from Rutherford scattering over the entire low energy region, especially near 330 kev, are also indicated. The alpha-particle and deuteron cross sections differ from customary results in that there is no indication of the rapid increase with bombarding energy usually attributed to barrier penetration factors. Anomalous effects appear at 330 and 900–1000 kev in the alpha-particle and deuteron reactions and, in addition to these energies, at 440 kev in the deuteron reaction. It is not clear whether the anomalies in the region 900–1000 correspond to interference effects from the 998-kev resonance or to resonance effects from a new level at 930 kev. A careful study of the alpha- and deuteron yield near 1087 kev was made with no indication of anomalous results similar to that in the elastic scattering. If an assignment of $J=0$ and even parity is made for the state at 1087 kev in B^{10}, then a strict selection rule forbidding alpha- or deuteron emission from this state follows. This is consistent with the known fact that this state does not radiate[4] to the

ground state of B^{10} and with the recent assignment of $J=3$ to the ground state since an octopole transition is then involved. The observed width is consistent with p-wave proton capture, formation of the state by s-wave capture not being possible since Be^9 has a spin of $\frac{3}{2}$. A more detailed theoretical discussion of these results will be given in a forthcoming publication by E. R. Cohen and R. F. Christy. This work was assisted by the joint program of the ONR and AEC.

[1] Snyder, Lauritsen, Fowler, and Rubin, Phys. Rev. **74**, 1564 (1948).
[2] Hole, Holtsmark, and Tangen, Naturwiss. **28**, 335 (1940).
[3] Curran, Dee, and Petrzilka, Proc. Roy. Soc. (London) **169**, 269 (1939).
[4] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 236 (1948).
[5] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949). The figures were prepared on the basis of 440 kev for the first resonance in $Li^7(p\gamma)$. A correction of +0.32 percent is necessary to change to the $F^{19}(pa', \gamma)$ scale.
[6] G. H. Henderson, Proc. Roy. Soc. (London) **109**, 157 (1925).
[7] G. H. Briggs, Proc. Roy. Soc. (London) **A114**, 341 (1927).
[8] E. Rutherford, Phil. Mag. **47**, 277 (1924).
[9] N. Bohr, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **XVIII**, 8.
[10] G. Mano, J. de phys. et rad. **5**, 628 (1934).
[11] C. B. Madsen and P. Venkateswarlu, Phys. Rev. **74**, 648 (1948).

Radioactive Silver Isotopes Produced by Photo-Disintegration of Cadmium*

R. B. Duffield and J. D. Knight
Department of Physics, University of Illinois, Urbana, Illinois
March 10, 1949

In the silver fraction isolated from cadmium, which had been irradiated with 21-Mev betatron x-rays, we have found evidence of two hitherto unassigned silver activities of half-lives 5.3 hr. and 20 min. Their counting rates, calculated to saturation and compared with those of the 3.2-hr. Ag 112 and the 7.6-day Ag 111 produced by (γ,p) reactions in the same irradiation, gave the relative yields shown in Table I.

The cadmium was irradiated in the form of reagent grade cadmium nitrate tetrahydrate; the silver fraction was precipitated as AgCl, dissolved and reprecipitated in the presence of inactive Cd^{++} solution to minimize contamination by the rather strong cadmium activities produced in the original sample.

Counts taken with the silver source mounted between the poles of a permanent magnet showed the 5.3-hr. and 20-min. activities to be β-emitters. The mass assignments of these periods were made by similar irradiations and treatment of samples of cadmium oxide enriched in Cd 114 and Cd 116.[1]

The decay curves are shown in Figs. 1 and 2.

The silver from the Cd 114 decayed with a half-life of 5.3 hr. over five half-lives, thus establishing that it was Ag 113 made by Cd 114 (γ,p). An aluminum absorption curve, evaluated by the Feather method, gave a beta-ray energy of 2.1 ± 0.2 Mev. No gamma-ray was detected. A period of similar half-life and beta-ray energy has been reported for a fission product silver by Turkevich.[2]

In the same manner, the 20-min. silver activity was found to be Ag 115 made by Cd 116 (γ,p). An aluminum absorption curve of the radiation showed the beta-ray energy to be approximately 3 Mev. No gamma-radiation was detected. Unfortunately, the low activity level of the sample prevented the positive identification of either the 43-day or 2.3-day Cd 115 daughters which would be expected to grow in. The half-life and beta-ray energy are very close to those reported for a fission-product silver by Turkevich[2] and by Seelmann-Eggebert and Strassman.[3]

Table I.

Activity	Half-life	Relative yield
Ag 111	7.6 day	2.7
Ag 112	3.2 hr.	1.00
Ag	5.3 hr.	1.15
Ag	20 min.	0.18

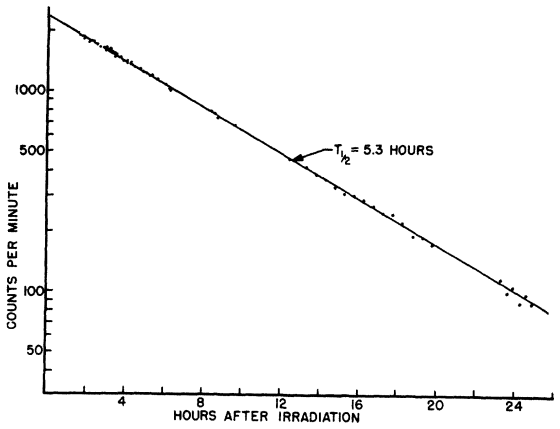

Fig. 1. Decay of silver activity produced by 21-Mev x-rays on cadmium containing 94 percent Cd 114.

Irradiation of the Cd 114 sample with fast neutrons from 10-Mev deuterons on beryllium produced a 2-min. β^--emitter which was chemically identified as silver. As a check on the possibility that this activity may have been due to 2.3-min. Ag 108 from a possible silver impurity in the cadmium, the latter was irradiated with slow neutrons and counted. No period of this half-life was found. A second possibility, that the 2-min. period may have been a metastable Cd 113m,[4] formed by Cd 114 $(n,2n)$, was excluded by the chemical separation and by the observed hardness of the electrons. It is probable, therefore, that the period we find is that of Ag 114 produced by Cd 114 (n,p).

We are indebted to Professor P. G. Kruger and the crew of the University of Illinois cyclotron and to Professor A. L. Hughes and the crew of the Washington University cyclotron for the neutron irradiations.

* Assisted by the joint program of the ONR and AEC.
[1] The enriched Cd 114 and Cd 116 used in this investigation were supplied by Carbide and Carbon Chemicals Corporation, Y-12 Plant, Oak Ridge, Tennessee, and obtained on allocation from the Isotopes Division of the AEC.
[2] A. Turkevich, Plutonium Project Report ANL-4010 quoted by G. T. Seaborg and I. Perlman, Rev. Mod. Phys. **20**, 585 (1948).
[3] W. Seelmann-Eggebert and F. Strassman, Zeits. F. Naturforschung **2a**, 80 (1947).
[4] A. C. Helmholz and C. L. McGinnis, Phys. Rev. **74**, 1559 (1948).

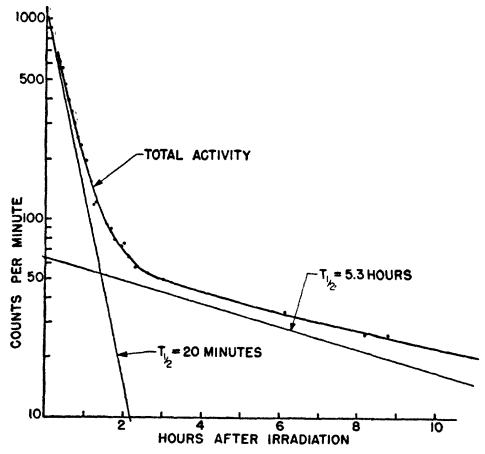

Fig. 2. Decay of silver activity produced by 21-Mev x-rays on cadmium containing 71 percent Cd 116, 18 percent Cd 114.