different reactions. This view is strengthened by the agreement of these results with those of Zlotowsky and Williams,[10] Rubin,[11] and Zaffarano, Kern, and Mitchell[12] on the energies of the gamma-rays which result from the capture of orbital electrons by Be^7. These authors obtained values, respectively, of 485 ± 5; 476 ± 10; and 474 ± 4 kev for this excited state of Li^7. Also, Rubin, Snyder, Lauritsen, and Fowler[13] have studied this level though the observation of inelastically scattered protons from Li^7. The result of their determination is 480 ± 2 kev. This is in excellent agreement with preliminary results in this Laboratory on the same process.

Note added in proof: In a recent article, F. N. D. Kurie and M. Ter-Pogossian report a value of 485 ± 5 kev for these gamma-rays [Phys. Rev. **74**, 677 (1948)].

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Use of Enriched Molybdenum in Cross-Section Measurements of the (p, n): (p, γ) and (d, n): $(d, 2n)$ Reactions

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Molybdenum of natural isotopic composition and molybdenum enriched in isotope 94 were subjected to bombardments with protons and deuterons. After monitoring, and from the saturation intensities and the nature of the decay of the radioactive substances produced, simultaneous equations were set up which yielded the relative values for the reaction cross sections.

For 5-Mev protons, $Mo^{94}(p, \gamma)$: $Mo^{95}(p, n)$: $Mo^{95}(p, \gamma)$: $Mo^{96}(p, n)=1$: 260: 40: 400. For 10-Mev deuterons, $Mo^{94}(d, n)$: $Mo^{95}(d, 2n)$: $Mo^{95}(d, n)$: $Mo^{96}(d, 2n)=1$: 13: 17: 2.5. The method is applicable to a wide range of elements.

INTRODUCTION

THE recent availability of enriched isotopes has provided a new approach to the measurement of relative cross sections of nuclei under charged particle bombardment.

The variation of the percent of the isotopic components in the bombarded targets enables one to set up a system of equations, each corresponding to a different activity, with the cross sections as unknowns. If the bombarding beam be properly monitored, these equations can be solved simultaneously to give the relative cross sections, provided that the details of the decay scheme of the resulting radioactive nuclei are known.

The present paper is illustrative of the above method. The relative cross sections for the reactions (p, n) to (p, γ) and (d, n) to $(d, 2n)$ leading to the 20-hour Tc^{95} and the 4.3-day Tc^{96} activities are measured by using natural molybdenum and enriched $Mo^{94}O_3$.**

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EXPERIMENTAL

Bombardments were made with 5-Mev protons and 10-Mev deuterons on (a) natural molybdenum metal (Hilger), (b) MoO_3 electromagnetically enriched in Mo^{92}, and (c) MoO_3 similarly enriched in Mo^{94}. The isotopic composition of the molybdenum samples is given in Table I.

Chemical separations were performed whenever necessary. The 2.7-hour activity which is known to be produced from Mo^{92} was used as a monitor of the beam current in different bombardments and also to correct for small differences in the weights of the materials in the samples. The decay of the activities was followed with a unifilar Wulf electrometer provided with an ionization chamber filled with freon gas at 20 lb. pressure above atmosphere. There was an adjustable electromagnet at the top of the ionization chamber so that the x-rays and the γ-rays could be studied separately after deflecting the charged particles away by the magnetic field.

DETAILS OF DISINTEGRATION PROCESS

In a typical bombardment of molybdenum with protons the saturation intensities for the charged particles, x-rays, and γ-rays in the 4.3-day half-life activity (Tc^{96}) were 8.40, 5.82, and 7.93 ionization units, respectively, and the corresponding figures in the 20-hour activity were 3.0, 3.45, and 2.45. Tc^{96} is known to decay partly by emission of a negative beta-particle[1] of maximum energy, 0.64 Mev, and partly by K-capture. There are also 0.92-Mev γ-rays. In the ionization chamber used, a beta-ray of maximum energy 0.64 Mev produced on the average about 84.5 times as much ionization as an x-ray quantum of 1.0A. Also in the chamber, the ionization produced by each γ-quantum of energy 0.92 Mev was about equal to that by the x-quantum. Thus to each beta-particle, there are $(5.82\times 84.5)/8.4=58.5$ x-ray quanta emitted. Again, there are $7.93/5.82=1.36$ γ-quanta per x-quantum. Combining, there are then approximately 60 x-quanta and 80 γ-quanta to each emitted beta-particle. Similarly, for the 20-hour[2] Tc^{95}, there are 7 x-quanta and 5 γ-quanta observed per charged particle. Both of these radioactive isotopes thus decay primarily by K-capture.

[1] D. Ewing, T. Perry, and R. McCreary, Phys. Rev. **55**, 1136 (1939).

[2] D. T. Eggen and M. L. Pool, Phys. Rev. **74**, 57 (1948).

TABLE I. Percent isotopic composition of bombarded target samples.

Sample	Mass numbers 92	94	95	96	97	98	100
Natural Mo	14.9	9.4	16.1	16.6	9.65	24.1	9.25
Enriched in 92	92.07	1.67	2.39	1.15	0.54	1.65	0.53
Enriched in 94	1.9	79.1	6.2	2.7	1.1	4.9	4.1

CALCULATION OF RELATIVE CROSS SECTIONS

The cross section for the production of a radioactive isotope from a target isotope is proportional to its saturation activity. The constant of proportionality, K, depends upon the beam current, geometry of the equipment, and on the radiations emitted.

In Table II are shown the saturation intensities obtained from typical bombardments. The values have been corrected to the same beam current and amount of material in the sample. The 2.7-hour activity was used as the monitor. The measurements were all made under identical geometrical arrangement.

From sets (1) and (2) of the table for the 20-hour activity, the following equations may be written:

$$9.00/K(20\text{H})=9.4\sigma_{94}{}^{p,\gamma}+16.1\sigma_{95}{}^{p,n},$$
$$3.62/K(20\text{H})=79.1\sigma_{94}{}^{p,\gamma}+6.2\sigma_{95}{}^{p,n},$$

where the coefficients of the σ's are the percent values in Table I. Solving, $\sigma_{94}{}^{p,\gamma}=0.00214/K(20\text{H})$ and $\sigma_{95}{}^{p,n}=0.56/K(20\text{H})$. Thus $\sigma_{95}{}^{p,n}/\sigma_{94}{}^{p,\gamma}=260$. This means that the 20-hour activity is produced 260 times as easily from Mo^{95} by the (p, n) reaction as from Mo^{94} by the (p, γ) reaction. Proceeding in a similar manner, analogous

TABLE II. Saturation ionization intensities of the 20-hour and 4.3-day activities obtained with targets of different isotopic composition.

Bombardment	Saturation intensity (ionization units) 20-hour half-life	4.3-day half-life
(1) Mo(natural)$+p$	9.0	22.2
(2) MoO_3 enriched in $Mo^{94}+p$	3.62	4.07
(3) MoO_3 enriched in $Mo^{94}+d$	14.6	14.7
(4) Mo(natural)$+d$	19.7	41.2
(5) MoO_3 enriched in $Mo^{92}+d$	1.115	5.44

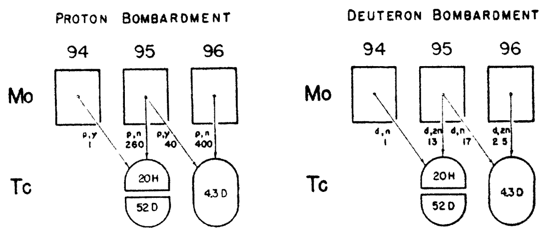

FIG. 1. Relative cross sections of $(p, n):(p, \gamma)$ and $(d, n):(d, 2n)$ reactions in Mo.

equations may be formed from the first four sets of data in Table II. The solutions are:

$$\sigma_{96}{}^{p,n}=1.22/K(4.3\text{D}),\quad \sigma_{95}{}^{p,\gamma}=0.126/K(4.3\text{D}),$$
$$\sigma_{95}{}^{d,2n}=1.17/K(20\text{H}),\quad \sigma_{94}{}^{d,n}=0.092/K(20\text{H}),$$
$$\sigma_{96}{}^{d,2n}=0.334/K(4.3\text{D}),\quad \sigma_{95}{}^{d,n}=2.23/K(4.3\text{D}).$$

The numerical values in the σ's come from measurements of the total radiation resulting from all the different kinds of radiations emitted by the particular activity formed.

It was seen in the preceding section that the 4.3-day and the 20-hour activities decay by emitting x-quanta 60 and 7 times as frequently, respectively, as by beta-emission. The main decay process is, therefore, by K-capture. The σ's can then be calculated by reducing the total intensities of ionization to that due to x-rays alone. If each x-quantum emitted is taken as standing for one disintegration, then all the K's become equal and the relative cross sections are immediately obtained.

For the 20-hour period, the ratio of the total ionization to that caused by x-rays was 9.0/3.45, and that for the 4.3-day period was 22.2/5.8. Based upon relative x-ray intensities, the following cross-section ratios are thus obtained:

$$\sigma_{95}{}^{p,\gamma}/\sigma_{95}{}^{p,n}=1/6.5$$

and

$$\sigma_{95}{}^{d,n}/\sigma_{95}{}^{d,2n}=1.3.$$

The various relative cross sections are graphically represented in Fig. 1. For 5-Mev proton bombardment the relative cross sections for the following reactions are, $\text{Mo}^{94}(p,\gamma):\text{Mo}^{95}(p,n):\text{Mo}^{95}(p,\gamma):\text{Mo}^{96}(p,n)=1:260:40:400$. For 10-Mev deuteron bombardment the cross sections are $\text{Mo}^{94}(d,n):\text{Mo}^{95}(d,2n):\text{Mo}^{95}(d,n):\text{Mo}^{96}(d,2n)=1:13:17:2.5$.

DISCUSSION

The additional set (5) of Table II may be used to check the accuracy of the relative values of the σ's obtained above. The predicted value of the saturation intensity in the 4.3-day activity in the enriched $\text{Mo}^{92}\text{O}_3+d$ bombardment is $(2.23\times 2.39+0.334\times 1.15)/K(4.3\text{D})=5.71/K(4.3\text{D})$, whereas the observed value is $5.44/K(4.3\text{D})$. The agreement is considered satisfactory.

It is to be noted that the cross-section ratios are based upon the observed intensities of the 20-hour Tc^{95} and 4.3-day Tc^{46} activities. The Tc^{95} isotope, however, is isomeric. Therefore, if the 52-day isomeric activity also be taken into consideration, the cross-section ratio for the reactions $\text{Mo}^{95}(p,n)$ to $\text{Mo}^{95}(p,\gamma)$ will be larger by a factor of perhaps 2 than the value 260/40 =6.5. The total cross-section ratio for the reactions $\text{Mo}^{95}(d,2n)$ to $\text{Mo}^{95}(d,n)$, which was observed to be 1:1.3, probably would be increased likewise.

It is sometimes found that the usual method of ascertaining a mass number of a newly observed radio-isotope by producing it from various cross reactions from neighboring elements is not applicable for lack of a suitable stable target isotope. In such circumstances, considerations of relative cross sections may be expected to be of use.

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