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Thermal Neutron Activation Cross Sections†

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The activation method of measuring slow neutron cross sections is discussed, in connection with the survey made at Argonne Laboratory. A table is given listing 131 activation cross sections of 65 elements and properties of the radio isotopes produced.

1. INTRODUCTION

MOST radioactive isotopes produced from natural isotopes by thermal neutron capture have half-lives and activities which have been observed in the laboratory. The charge-to-mass ratio of these artificially produced radioactive isotopes is usually too low for stability, so they emit β^--rays.[1] When the decay is complete, one β^--ray will have been emitted for every neutron which was captured by the original stable nucleus. Thus the counting of β^--rays enables the determination of the number of neutrons captured by certain isotopes. If, in addition, the thermal neutron flux is known, and the number of atoms doing the capturing is measured, the thermal neutron capture cross section can be calculated. This is the essence of the activation method of measuring neutron cross sections.[2] At the Argonne Laboratory in June, 1943 a program was started to measure as many thermal neutron activation cross sections as possible. This paper describes the experimental method and lists the cross sections measured. The work was all done on the graphite pile except that starting in July, 1944, irradiations were begun in the heavy-water pile.

Several of the 137 different half-lives produced by slow neutron capture gave rise to daughter activities, since the isotopes produced by β^--decay were not stable in these cases. An example is 26-min. $_{46}Pd^{111}$ produced by slow neutrons from $_{46}Pd^{110}$. A 7.5-day $_{47}Ag^{111}$ daughter activity was

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The work was completed in October, 1944. It was done under contract between the Manhattan District, Corps of Engineers, War Department, and the University of Chicago, at the Argonne Laboratory.

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[1] There are also several cases of positron emission, K-capture, and isomeric transition.

[2] The first surveys of slow neutron cross sections by the activation method were made independently by Franco Rasetti, Phys. Rev. **58**, 869 (1940) and R. D. O'Neal and M. Goldhaber *ibid.* **59**, 102 and 109 (1941).

formed, but $_{48}\text{Cd}^{111}$ is stable, ending the chain. The number of neutrons captured by the $_{46}\text{Pd}^{11}{}_{0}$ was computed from the β^{-}-ray count of both $_{46}\text{Pd}^{111}$ and $_{47}\text{Ag}^{111}$.

2. DESCRIPTION OF MEASUREMENTS

A. Thermal Activation Formula $\nu = nv\sigma N$

When a thin detector is placed in the interior of a diffusing medium the number of thermal neutron captures per unit time is given by[3]

$$\nu = nv\sigma N$$

where nv = thermal neutron flux, σ = thermal neutron cross section (follows $1/v$ law), N = number of atoms of detector. Thus to calculate σ, the problem is to measure ν, nv, and N. Note that since σ is proportional to $1/v$, ν is really proportional to neutron density n.

B. Measurement of ν

To measure the number of neutron captures per unit time, the number of β-disintegrations per unit time was measured after the irradiation had been completed, and the detector foil observed to decay with the proper half-life. With the aid of the radioactive-decay laws, the number of β-disintegrations observed at a given decay time was reduced to the number of β-disintegrations at saturation, which equals the number of neutron captures per unit time. The β-disintegrations were recorded on either a Duraluminum (51 mg/cm^2) or a mica-window (4 mg/cm^2) Geiger counter. Beta-rays of maximum energy less than 0.85 Mev were always counted on the latter counter. The counting rate of the Geiger counter was converted into β-disintegrations per unit time by correcting for the geometrical and absorption loss of β-rays. The geometrical factor was computed by using UX_{II} and RaE β-ray standards. Since β-rays in the early part of their range are absorbed exponentially, the external and self-absorption loss of β-rays were computed with this exponential relationship. Thus the total efficiency of the counter was taken as

$$E = G\exp\left(-\frac{\mu}{\rho}x\right)$$

where G = geometry factor, μ/ρ = mass-absorption coefficient for the β-rays, and x = thickness of counter wall, foil cover, and half of foil thickness. For the UX_{II} and RaE β-ray standards, the mass-absorption coefficients were found to be 6.1 and 16.9 cm^2/g Al, respectively, and using these values in the above formula the Duraluminum counter-wall thickness was found to be 51 mg/cm^2. This is equivalent to aluminum of 7-mil

TABLE I. Comparison of activation with transmission cross sections.

Element	Half-life	σ_{capture} (from activation) (barns)	$\sigma_{\text{total}} - \sigma_{\text{scattering}}$* (from transmission) (barns)	Ratio: $\dfrac{\sigma_{\text{capture}} \text{ from total activation}}{\sigma_{\text{capture}} \text{ from transmission}}$
Rh	44 s	150		
	4.2 m	12.8		
	Total	162.8	150	1.09
Ag	22 s	51.3		
	2.3 m	25.3		
	225 d	1.1		
	Total	77.7	59.2	1.31
In	13 s	54		
	54 m	150		
	48 d	2.7		
	Total	206.7	189	1.09
Au	2.7 d	105	96	1.09

* $\sigma_{\text{scattering}}$ assumed to be 5×10^{-24} cm^2 and σ_{total} is for a neutron speed of 2200 meters/sec.

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[3] H. A. Bethe, Rev. Mod. Phys. 9, 132 (1937).

thickness. For every different activity observed, the mass-absorption coefficient μ/ρ of the β-rays was measured.

C. Measurement of *nv*

Every substance irradiated in the thermal column was accompanied by a standard monitor (described below) for measuring *nv*. After calibration, *nv* was obtained by simply multiplying the saturated activity of the *nv* monitor by the calibration factor.

The calibration of the *nv* monitors was done by three methods. One calibration was made by using Mr. Kubitschek's apparatus.[4] This measures *nv* directly with BF_3 counter, and includes measurements of the cross section of the boron-trifluoride gas used, the velocity of the neutrons and the number of $B^{10}(n, \alpha)$ disintegrations per mole of gas and per unit area of neutron beam. This calibration made the cross sections come out 1.06 ± 0.03 lower than from the first standardization and was considerably more accurate.

Another check on the *nv* monitors was made by comparing the activation cross sections for the elements $_{45}Rh$, $_{47}Ag$, $_{49}In$, $_{79}Au$ with accurate transmission measurements made by Fermi (see Table I). These results made the cross sections come out by a factor 1.09 lower than the first standardization. These last two calibrations were for 2200-meters per second neutrons so that the cross sections measured were then automatically for 2200-meters per second neutrons.

The use of standard indium, manganese and copper monitors enabled all ranges of *nv* to be measured. The ranges for which *nv* could be conveniently measured were:

Indium	1×10^2 to 1×10^6 neutrons/cm²-sec.,
Manganese	2×10^3 to 5×10^6,
Copper	2×10^5 to 1×10^9,
Silver	1×10^7 to 2×10^{11}.

The practical limit of irradiation which could be given to substances in the graphite pile thermal column was 10^{11} neutrons/cm². When greater irradiations were required, the substances were irradiated in the center of the pile.

The number of neutrons/cm²-kwh had been determined by standard indium foils measured at the same time that the watts being dissipated were determined from heating of a central uranium lump. A rough check on this value was made by computing the number of fissions necessary to give 1-watt power dissipation. Finally, this value was checked with the standard copper monitors which have no appreciable resonance activation.

Some substances were left in the center of the graphite pile for as long as two months. The number of kwh for any irradiation was determined from the gold-foil pile monitors, described by Mr. Sturm.

D. Measurement of *N*

The number of atoms of detector, *N*, was measured simply by weighing the foil on an analytical balance and dividing by the molecular weight of the compound. Substances which were not reagent grade were assayed by Mr. Bane's group of the Chemistry Division. For β-ray counting the powders were brushed on Scotch Tape over an area of 5 to 7.5 cm². The Scotch Tape was weighed before and after deposition of the powder and the accuracy of weighing was found to be 0.2 mg. The β-ray foils ranged in weight from 2 mg to ≈ 200 mg.

E. Types of Foils Used

For β-ray counting, foils were made by brushing a thin layer of the desired compound (ground up finely) onto Scotch Tape. The powder was spread over a measured area by means of a mask, and then covered with another layer of Scotch Tape. For long half-life activities, the powder was irradiated while spread out in a Lusteroid test tube. For short half-life activities it was necessary to make up the foil before irradiation, and irradiate together with the Scotch Tape covering. In a few cases of short half-life combined with small cross section it was necessary to irradiate a blank Scotch Tape foil and subtract from the measured foil the activity induced in the blank foil.[5] When very soft β-rays were being detected (example: $_{16}S^{35}$ with $\mu/\rho = 290$ cm²/g) the active deposit had no Scotch Tape cover.

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[4] A description of standardization of neutron flux will be published in the Plutonium Project Report.

[5] The short half-life activity in Scotch Tape could be ascribed to 2.4-min. $_{13}Al^{28}$ and 14.8-hr. $_{11}Na^{24}$.

Metallic elements which could be obtained in a malleable state were prepared by rolling the pure element to the desired thickness (examples: $_{46}$Pd, $_{47}$Ag, $_{48}$Cd, $_{49}$In, and $_{50}$Sn).

Elements like gadolinium and samarium which have a very high total neutron capture cross section were irradiated by diluting the rare-earth oxide powder one-hundred fold with BeO powder. This dilution prevented self-absorption of neutrons, but reduced the accuracy somewhat because it was hard to mix the two powders homogeneously.

For counting x-rays and γ-rays, where a greater foil thickness was desired, the active substance was pressed in the form of a pellet in a 1-inch circular die with the aid of a hydraulic press. These pellets were from $\approx\frac{1}{2}$ mm to 4 mm thick. Substances which did not press easily could be rendered so by adding 1 part of inactive sulfur to 2 parts of the active substance.

F. Measurement of ν for x-rays and γ-rays

For the few isotopes which decayed by K-capture, the disintegration rate was determined by detecting either the K_α X-rays of the next lower element or by detecting the γ-rays when the disintegration energy levels were well known. The x-rays were always detected using the technique of Alvarez, i.e., by taking absorption coefficients in the proper adjacent elements, so as to display K-critical absorption edge, thus identifying the element emitting the x-ray.

The efficiency of the counter for different energy x-rays and gamma-rays was computed to enable a determination of the disintegration rate. The γ-ray efficiency of the counter was found experimentally to be $\frac{1}{2}$ percent for the 0.5-Mev annihilation γ-rays from $_{29}$Cu^{64} and was assumed to be proportional to the γ-ray energy.[6]

G. Discussion of Errors

The measurement of cross sections by the activation method is not an accurate measurement. The following discussion of the errors involved in the measurement of ν, $n\nu$, N and τ shows that the accuracy is limited 10 to 20 percent. With this in mind, the program at the Argonne Laboratory was aimed at a rapid survey of all the cross sections, rather than a precise measurement of a few of them.

Errors connected with the measurement of ν by detecting β-disintegrations are as follows: Gamma-rays which accompany the β-disintegration give rise to conversion electrons which the Geiger-counter counts as β-particles. This effect is more pronounced for soft γ-rays and high atomic number. The difficulty is that the fractional number of conversion electrons compared to the total β-ray spectrum is unknown for almost all radioactive isotopes. In one of the worst possible cases, that of $_{79}$Au^{198}, it was known that the conversion electrons comprised 14 percent of the β-ray spectrum. This correction was used in computing the cross section of $_{79}$Au^{197}, but was unknown for other isotopes and may make some of the calculated cross sections too high by as much as $\sim$15 percent. Note that isotopes which had β-rays of $\approx$1-Mev maximum energy or greater, and also had soft γ-rays of $\approx$0.4 Mev or less, were counted on the Duraluminum counter, which absorbed the conversion electrons completely.

The inaccuracy of the measurement of the mass-absorption coefficient of the β-rays and the extrapolation of the absorption of the β-rays in the counter wall to zero wall thickness give rise to errors as high as 15 percent.

Gamma-rays, when they accompany the β-disintegration, are also counted by the Geiger counter. But the sensitivity of the Geiger counter of 1-Mev gamma-rays is only 1 percent, so that gamma-rays may make the calculated cross section high by not more than $\sim$3 percent.

The calibration of the Geiger counters (geometrical factor and wall thickness) was done with four UX$_{II}$ standards and three RaE β^--ray standards. The standards were prepared by weight and α-counting, respectively, and the average deviation in β^--counting rates was $\sim$4 percent, so that the calculated cross section could be rendered either high or low by this amount.

Geiger counters themselves change their sensitivity and plateau region with time. Even though β^--ray standards were always used to check the operation of the Geiger counters, it has been found by experience that individual foil counting rates check to only 2 percent.

Errors connected with the measurement of $n\nu$,

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[6] F. Norling, Phys. Rev. **58**, 277 (1940).

TABLE II. Thermal neutron activation cross sections.

Item No.	Natural isotope (1)	Natural abundance (percent) (2)	Half-life of the $A+1$ isotope (3)	Isotopic cross section (barns) (4)	Natural atom cross section (barns) (5)	Probable error (percent) (6)	Mass-absorption coefficient of β-rays in cm^2/g of aluminum (7)	Substance used (8)	Place of irradiation (9)	(10)	Remarks (11)
1	$_8O^{18}$	0.20	31 sec.	0.00022	0.000,000,4	±20	2.56	Distilled H_2O	Pile	*	Cf. Phys. Rev. **70**, 561 (1946).
2	$_9F^{19}$	100	12 sec.	0.0094	0.0094	±20	0.93	CaF_2	Pile		
3	$_{11}Na^{23}$	100	14.8 hr.	0.63	0.63	±20	8.1	NaCl Na_2CO_3	Pile		σ may be high due to conversion electrons.
4	$_{12}Mg^{26}$	11.1	10.2 min.	0.048	0.0054	±20	6.1	Mg-metal powder	Pile		
5	$_{13}Al^{27}$	100	2.4 min.	0.21	0.21	±20	2.5	Al foil	Thermal column		
6	$_{14}Si^{30}$	4.2	170 min.	0.116	0.00485	±20	8	Si metal powder	Pile		
7	$_{15}P^{31}$	100	14.3 d	0.23	0.23	±20	5.3	Red P powder	Pile		
8	$_{16}S^{34}$	4.2	87.1 d	0.26	0.011	±20	290	S flowers	Pile	*	
9	$_{17}Cl^{35}$	75.4	87.1 d for $_{16}S^{35}$	0.169	0.13	±20	290	NH_4Cl NaCl	Thermal column	*	This reaction $_{17}Cl^{35}(n, p)_{16}S^{35}$ goes with thermal neutrons.
10	$_{17}Cl^{37}$	24.6	37 min.	0.56	0.137	±20	8.7 3.2	NaCl	Thermal column		Two groups of beta-rays.
11	$_{19}K^{41}$	6.61	12.4 hr.	1.0	0.067	±20	2.56	K_2CO_3 $K_2C_2O_4H_2O$	Pile		
12	$_{20}Ca^{40}$	96.96	8.5 d	<0.000125	<0.00012	±40	*K*-capture X-rays	CaF_2 $CaCO_3$ $Ca(NO_3)_2$	Pile		See Table III.
13	$_{20}Ca^{44}$	2.06	180 d	0.63	0.013	±20	128 7.5	CaF_2	Pile		Two groups of β-rays. Ratio of soft to hard ~450
14	$_{20}Ca^{48}$	0.19	30 min.	0.55	0.00105	±20	~5.8	CaF_2 $CaCO_3$	Pile		See Table III. Nuclear isomer.
15	$_{20}Ca^{48}$	0.19	150 min.	0.205	0.00039	±20	5.8	CaF_2 $CaCO_3$	Pile		See Table III. Nuclear isomer.
16	$_{21}Sc^{45}$	100	85 d	22	22	±20	71	Sc_2O_3 $K_3Sc(SO_4)_3$	Pile		See Table III.
17	$_{22}Ti^{50}$	5.34	6 min.	0.141	0.0075	±20	5.4	Ti-metal powder	Pile		Half-life previously reported 2.8 min. We find 6 min. over 3 half lifes.
18	$_{22}Ti^{50}$	5.34	72 d	0.039	0.0021	±20	65	TiO_2	Pile		Nuclear isomer.
19	$_{23}V^{51}$	100	3.9 min.	4.50	4.50	±20	3.9	V_2O_5	Thermal column		
20	$_{24}Cr^{50}$	4.49	26.5 d	11	0.50	±40	*K*-capture conversion electrons	Cr_2O_3	Pile		See Table IV.
21	$_{24}Cr^{54}$	2.30	1.3 hr.	~0.0061	~0.00014	±40	~8.3	Cr_2O_3	Pile		Reported half-lifes of 1.6 to 2.3 hr. We find weak activity of 1.3 hours.
22	$_{25}Mn^{55}$	100	2.59 hr.	10.7	10.7	±20	4.85	Mn-metal powder	Thermal column		
23	$_{26}Fe^{58}$	0.28	47 d	0.36	0.0010	±20	43	Fe_2O_3	Pile	*	
24	$_{27}Co^{59}$	100	10.7 min.	0.66	0.66	±20	147 12.9	Co_2O_3	Thermal column		See Table III.
25	$_{27}Co^{59}$	100	5.3 yr.	21.7	21.7	±20	79	Co_2O_3	Pile		
26	$_{28}Ni^{64}$	0.88	2.6 hr.	1.96	0.0173	±20	7.3	Ni-metal NiO	Thermal column		
27	$_{29}Cu^{63}$	70.13	12.8 hr.	2.82	2.0	±20	33	Cu-metal powder	Thermal column		

TABLE II.—*Continued.*

Item No.	Natural isotope (1)	Natural abundance (percent) (2)	Half-life of the $A+1$ isotope (3)	Isotopic cross section (barns) (4)	Natural atom cross section (barns) (5)	Probable error (percent) (6)	Mass-absorption coefficient of β-rays in cm²/g of aluminum (7)	Substance used (8)	Place of irradiation (9)	(10)	Remarks (11)
28	${}_{29}Cu^{65}$	29.87	5 min.	1.82	0.56	±20	3.2	Cu-metal powder	Thermal column		
29	${}_{30}Zn^{64}$	50.9	250 d	0.51	0.26	±20	107	Zn foil	Pile		See Table III.
30	${}_{30}Zn^{68}$	17.4	57 min.	1.09	0.19	±20	17.1	Zn foil	Thermal column		Nuclear isomer.
31	${}_{30}Zn^{68}$	17.4	13.8 hr.	0.31	0.054	±20	10.3	Zn foil	Pile		Nuclear isomer.
32	${}_{31}Ga^{69}$	61.2	20 min.	1.40	0.855	±20	6.5	Ga_2O_3	Thermal column		
33	${}_{31}Ga^{71}$	38.8	14.1 hr.	3.36	1.30	±20	9.6	Ga_2O_3	Pile		
34	${}_{32}Ge^{70}$	21.2	40 hr.	0.073	0.0155	±20	25.7	GeO_2	Pile		Positron activity.
35	${}_{32}Ge^{70}$	21.2	11 d	~0.45	~0.095	±40	*K*-capture X-rays	GeO_2	Pile	*	See Table III.
36	${}_{32}Ge^{74}$	37.1	89 min.	0.38	0.14	±20	13.3	GeO_2	Pile		
37	${}_{32}Ge^{76}$	6.5	12 hr.	0.085	0.0055	±20	7.8	GeO_2	Pile		
38	${}_{33}As^{75}$	100	26.8 hr.	4.2	4.2	±20	4.3	As_2O_3	Thermal column		
39	${}_{34}Se^{74}$	0.9	115 d	22	0.2	±40	*K*-capture X-rays	Se-metal powder	Pile	*	See Table III.
40	${}_{34}Se^{78,80}$		19 min.		0.23	±20	7.9	Se-metal powder	Thermal column		Nuclear isomer.
41	${}_{34}Se^{78,80}$		57 min.		0.017	±20	7.9 for daughter	Se-metal powder	Pile		Nuclear isomer.
42	${}_{34}Se^{82}$	9.3	30 min.	0.060	0.0056	±20	15.6 for ${}_{35}Br^{83}$	Se-metal powder	Pile		σ calculated by observing 140 min. ${}_{35}Br^{83}$.
43	${}_{35}Br^{79}$	50.6	18 min.	8.1	4.1	±20	6.4	KBr	Thermal column		Nuclear isomer.
44	${}_{35}Br^{79}$	50.6	4.4 hr.	2.76	1.39	±20	5.3	KBr	Thermal column		Nuclear isomer.
45	${}_{35}Br^{81}$	49.4	34 hr.	2.25	1.11	±20	35	KBr	Pile		
46	${}_{37}Rb^{85}$	72.8	19.5 d	0.72	0.52	±20	6.7	$RbNO_3$	Pile		
47	${}_{37}Rb^{87}$	27.2	17.5 min.	0.122	0.033	±20	2.6	$RbNO_3$	Thermal column		
48	${}_{38}Sr^{86}$	9.86	2.7 hr.	1.29	0.128	±20	9.6 conversion electrons	$Sr(NO_3)_2$	Thermal column	*	See Table III.
49	${}_{38}Sr^{88}$	82.56	55 d	0.0050	0.00415	±20	8.8	$SrCO_3$	Pile		
50	${}_{39}Y^{89}$	100	60 hr.	1.24	1.24	±20	4.7	$Y_2(SO_4)_3$	Pile		
51	${}_{40}Zr^{92}$	22	63 d	0.33	0.073	±40	60	Zr metal $ZrO(NO_3)_2$	Pile		Isotopic assignment not certain.
52	${}_{40}Zr^{94}$	17	17.0 hr.	0.053	0.009	±20	9.4	Zr-metal powder	Pile		Gives rise to 75-min. ${}_{41}Cb^{75}$.
53	${}_{40}Zr^{96}$	1.5	6 min.	~1.07	~0.016	±40	~5	Zr-metal powder	Thermal column		
54	${}_{41}Cb^{93}$	100	6.6 min.	~1.0	~1.0	±40	9.5	Cb metal Cb_2O_5	Thermal column		Decay of ${}_{41}Cb^{94}$ is mainly by *K*-capture or isomeric transition. See Table III.
55	${}_{42}Mo^{100}$	9.25	19 min.	0.475	0.044	±20	10	MoO_3	Pile		
56	${}_{42}Mo^{98}$	24.1	67 hr.	0.415	0.10	±20	11.7	MoO_3	Pile		
57	${}_{42}Mo^{92}$?		7 hr.		<0.001	±40	*K*-capture?	MoO_3	Pile		No 7-hr. activity was found.
58	${}_{44}Ru^{102,104}$		4 hr.		0.122	±20	11	Ru-metal powder	Pile		

TABLE II.—*Continued.*

Item No.	Natural isotope (1)	Natural abundance (percent) (2)	Half-life of the $A+1$ isotope (3)	Isotopic cross section (barns) (4)	Natural atom cross section (barns) (5)	Probable error (percent) (6)	Mass-absorption coefficient of β-rays in cm^2/g of aluminum (7)	Substance used (8)	Place of irradiation (9)	(10)	Remarks (11)
59	${}_{44}\mathrm{Ru}?$		37 hr.		0.15	±20	40	Ru-metal powder	Pile	*	Other investigators have reported a 20 hr. half life.
60	${}_{44}\mathrm{Ru}?$		40 d		0.37	±20	161	Ru-metal powder	Pile	*	Other investigators reported 45±5 days.
61	${}_{45}\mathrm{Rh}^{103}$	100	44 sec.	137	137	±10	3.9	Rh-metal powder	Thermal column		Nuclear isomer.
62	${}_{45}\mathrm{Rh}^{103}$	100	4.2 min.	11.6	11.6	±10	4.4	Rh-metal powder	Thermal column		Nuclear isomer.
63	${}_{46}\mathrm{Pd}^{108}$	26.8	13 hr.	11.2	3.0	±20	16.1	Pd-metal foil	Thermal column		
64	${}_{46}\mathrm{Pd}^{110}$	13.5	26 min.	0.39	0.0525	±20	6.9	Pd-metal foil	Thermal column		Gives rise to 7.5 day ${}_{47}\mathrm{Ag}^{111}$.
65	${}_{47}\mathrm{Ag}^{107}$	51.9	2.3 min.	44.3	23	±20	6.7	Ag-metal foil	Thermal column		
66	${}_{47}\mathrm{Ag}^{109}$	48.1	22 sec.	97.0	46.6	±20	2.9	Ag-metal foil	Thermal column		
67	${}_{47}\mathrm{Ag}^{109}$	48.1	225 d	2.3	1.1	±20	36.5	Ag-metal foil	Pile		σ computed assuming one particle per disintegration. Resonance contribution to the cross section is suggested by the work of M. Goldhaber, Phys. Rev. **70**, 89 (1946).
68	${}_{48}\mathrm{Cd}^{114}$	28.0	2.5 d	1.1	0.30	±20	10.7	Cd-metal foil	Pile		Gives rise to 4.1 hr. ${}_{49}\mathrm{In}^{115*}$
69	${}_{48}\mathrm{Cd}^{114}$	28.0	43 d	0.14	0.040	±20	7.0	Cd-metal foil	Pile	*	Cf. Seren *et al.*, Phys. Rev. **71**, 409 (1947).
70	${}_{48}\mathrm{Cd}^{116}$	7.3	3.75 hr.	1.4	0.10	±20	8.5	Cd-metal foil	Pile		Gives rise to 2 hr. ${}_{49}\mathrm{In}^{117}$.
71	${}_{48}\mathrm{Cd}?$		2 min.		0.05	±20	5.7	Cd-metal CdO	Pile		
72	${}_{49}\mathrm{In}^{113}$	4.5	48 d	56.0	2.52	±10	6.35 for 72 sec. daughter	In-metal foil	Thermal column		Gives rise to 72-sec. ${}_{49}\mathrm{In}^{114}$.
73	${}_{49}\mathrm{In}^{115}$	95.5	13 sec.	51.8	49.5	±10	5.4	In-metal foil	Thermal column		Nuclear isomer.
74	${}_{49}\mathrm{In}^{115}$	95.5	54 min.	144.6	138	±10	17.2	In-metal foil	Thermal column		Nuclear isomer.
75	${}_{50}\mathrm{Sn}^{112}$	1.1	105 d	~1.1	~0.012	±40	*K*-capture X-rays	Sn-metal foil	Pile	*	See Table III.
76	${}_{50}\mathrm{Sn}^{124}$	6.8	9 min.	0.574	0.039	±20	5.2	Sn-metal foil	Pile		
77	${}_{50}\mathrm{Sn}^{<125}$		40 min.		0.0142	±20	13.6	Sn-metal foil	Pile		
78	${}_{50}\mathrm{Sn}^{<125}$		26 hr.		0.072	±20	75	Sn-metal foil	Pile		
79	${}_{50}\mathrm{Sn}^{<125}$		10 d		0.009	±20	66	Sn-metal foil	Pile		
80	${}_{50}\mathrm{Sn}^{<125}$		400 d		0.018	±20	29	Sn-metal foil	Pile		
81	${}_{51}\mathrm{Sb}^{121}$	56	2.8 d	6.8	3.8	±20	~10	Sb-metal powder	Pile		
82	${}_{51}\mathrm{Sb}^{123}$	44	60 d	2.5	1.1	±20	14	Sb-metal powder	Pile		
83	${}_{52}\mathrm{Te}^{126}$	19.0	9.3 hr.	0.78	0.15	±20	27.2	Te-metal powder	Pile	*	Nuclear isomer.
84	${}_{52}\mathrm{Te}^{126}$	19.0	90 d	0.073	0.014	±20	~24	Te-metal powder	Pile	*	Nuclear isomer gives rise to 9.3-hr. Te^{127}.

TABLE II.—*Continued.*

Item No.	Natural isotope (1)	Natural abundance (percent) (2)	Half-life of the $A+1$ isotope (3)	Isotopic cross section (barns) (4)	Natural atom cross section (barns) (5)	Probable error (percent) (6)	Mass-absorption coefficient of β-rays in cm^2/g of aluminum (7)	Substance used (8)	Place of irradiation (9)	(10)	Remarks (11)
85	$_{52}\mathrm{Te}^{128}$	32.8	72 min.	0.133	0.0436	±20	12.6	Te-metal powder	Pile	*	Nuclear isomer.
86	$_{52}\mathrm{Te}^{128}$	32.8	32 d	0.0154	0.00504	±20	~12.6	Te-metal powder	Pile	*	Nuclear isomer. Gives rise to 72-min. Te^{129}.
87	$_{52}\mathrm{Te}^{130}$	33.1	25 min.	0.222	0.0735	±20	7.1	Te-metal powder	Thermal column		Nuclear isomer. See Table III.
88	$_{52}\mathrm{Te}^{130}$	33.1	30 hr.	<0.008	<0.003	±40	~7.1	Te-metal powder	Pile		Nuclear isomer. Gives rise to 25-min. Te^{131}.
89	$_{53}\mathrm{I}^{127}$	100	25 min.	6.25	6.25	±20	5.33	$\mathrm{PbI_2}$	Thermal column		
90	$_{55}\mathrm{Cs}^{133}$	100	3 hr.	0.016	0.016	±20	~8	$\mathrm{CsNO_3}$	Pile		Nuclear isomer.
91	$_{55}\mathrm{Cs}^{133}$	100	1.7 yr.	25.6	25.6	±20	23	$\mathrm{CsNO_3}$	Pile		Nuclear isomer.
92	$_{56}\mathrm{Ba}^{138}$	71.66	86 min.	0.511	0.367	±20	7.9	$\mathrm{BaO_2}$	Thermal column		
93	$_{57}\mathrm{La}^{139}$	100	40 hr.	8.4	8.4	±20	9.6	La metal $\mathrm{La(NH_4)_2(NO_3)_5}$	Pile		
94	$_{59}\mathrm{Pr}^{141}$	100	19.3 hr.	10.1	10.1	±20	5.4	$\mathrm{Pr_4O_7}$	Thermal column		
95	$_{62}\mathrm{Sm}$?		21 min.		1.10	±20	8.25	$\mathrm{Sm_2O_3}$	Thermal column		
96	$_{62}\mathrm{Sm}^{152}$	26	46 hr.	138	35.8	±20	27.5	$\mathrm{Sm_2O_3}$	Thermal column		
97	$_{62}\mathrm{Sm}$?		60 d		<0.008	±40		$\mathrm{Sm_2O_3}$	Pile		See Table III.
98	$_{63}\mathrm{Eu}^{151}$	49.1	9.2 hr.	1380	681	±20	6.7	Eu oxalate	Thermal column		See Table III.
99	$_{63}\mathrm{Eu}^{151,153}$		5–8 yr. (6.5 yr.)		390	±20	26	Eu oxalate	Pile		See Table III. This long period activity is due to both Eu^{152} and Eu^{154}. See M. G. Ingram and R. J. Hayden, Phys. Rev. **71**, 130 (1947).
100	$_{64}\mathrm{Gd}$?		9.5 hr.		2.3	±20	8.7	$\mathrm{Gd_2O_3}$	Pile		Reported half-life is 8 hr.
101	$_{64}\mathrm{Gd}$?		20 hr.		~0.9	±40	~20	$\mathrm{Gd_2O_3}$	Pile	*	May be due to impurities in $\mathrm{Gd_2O_3}$.
102	$_{64}\mathrm{Gd}$?		8.6 d		~0.6	±40	~30	$\mathrm{Gd_2O_3}$	Pile		May be due to impurities in $\mathrm{Gd_2O_3}$.
103	$_{64}\mathrm{Gd}$?		160 d		<0.25	±40		$\mathrm{Gd_2O_3}$	Pile		No 160-day activity was found during 210 days decay.
104	$_{65}\mathrm{Tb}^{159}$	100	3.9 hr.	10.7	10.7	±20	~10	$\mathrm{Tb_4O_7}$	Thermal column		
105	$_{66}\mathrm{Dy}^{164}$	27.6	140 min.	2620	725	±10	12.4	$\mathrm{Dy_2O_3}$	Thermal column		Cadmium ratio is 97±7.
106	$_{66}\mathrm{Dy}^{164}$	27.6	1.25 min.	120	33	±40	~50	$\mathrm{Dy_2O_3}$	Thermal column		Our cross section assumes beta-ray decay and is probably erroneous because the later work of Ingraham, Shaw, Hess, and Hayden, Phys. Rev. **72**, 515 (1947) indicates a soft gamma-ray decay (isomeric transition to the 140-min. activity).
107	$_{67}\mathrm{Ho}^{165}$	100	30 hr.	59.6	59.6	±20	7.1	$\mathrm{Ho_2O_3}$	Thermal column		Half-life sometimes given as 35 hr., but we find 30 hr.
108	$_{69}\mathrm{Tm}^{169}$	100	105 d	106	106	±20	17.3	$\mathrm{Tm_2O_3}$	Thermal column		

TABLE II.—*Continued.*

Item No.	Natural isotope (1)	Natural abundance (percent) (2)	Half-life of the $A+1$ isotope (3)	Isotopic cross section (barns) (4)	Natural atom cross section (barns) (5)	Probable error (percent) (6)	Mass-absorption coefficient of β-rays in cm^2/g of aluminum (7)	Substance used (8)	Place of irradiation (9)	(10)	Remarks (11)
109	$_{71}$Lu^{175,176}		3.4 hr.		15.9	±20	12.0	Lu_2O_3	Thermal column		
110	$_{71}$Lu^{176}	2.5	6.6 d	3640	91.0	±20	50.0	Lu_2O_3	Thermal column		Refer to Ingram *et al.*, Phys. Rev. **71**, 270 (1947).
111	$_{72}$Hf^{180}	35.14	46 d	10.0	3.5	±20	47.0	$HfOCl \cdot 7H_2O$	Pile		Listed half-life is 55 days. We find 46±3 days over 2½ half lifes.
112	$_{73}$Ta?		16.2 min.		0.034	±20	85	Ta-metal foil	Thermal column	*	See Table III. Cf. Seren, Friedlander, and Turkel, Phys. Rev. **72**, 163 (1947).
113	$_{73}$Ta^{181}	100	117 d	20.6	20.6	±20	46	Ta-metal foil	Thermal column		$\int \sigma \frac{dE}{E} = 800$ See Table III.
114	$_{74}$W^{184}	30.1	77 d	2.12	0.64	±20	70	W-metal powder	Pile		
115	$_{74}$W^{186}	29.8	24.1 hr.	34.2	10.2	±20	20.7	W-metal powder	Thermal column		
116	$_{75}$Re^{185}	38.2	90 hr.	101	38.5	±20	16.9	Re-metal powder	Thermal column		
117	$_{75}$Re^{187}	61.8	18 hr.	75.3	46.5	±20	5.5	Re-metal powder	Thermal column		
118	$_{76}$Os^{190}	26.4	30 hr.	2.50	0.66	±20	14.5	Os-metal powder	Pile		Literature half-lives are 29 hr. and 32±2 hr. We find 30 hr.
119	$_{76}$Os^{192}	41.0	17 d	5.34	2.19	±20	187	Os-metal powder	Pile		
120	$_{77}$Ir^{191}	38.5	1.5 min.	260	100	±40	~28 Isomeric transition	Ir-metal powder	Thermal column		This isomer decays into the 70 days activity listed below. See Table III.
121	$_{77}$Ir^{191}	38.5	70 d	1000	388	±20	33.5	Ir-metal powder	Thermal column		Half-life in literature is 60 days. We find 70±2.5 days. The cross section listed here *includes* the contribution from 1.5-minute activity. See Table III.
122	$_{77}$Ir^{193}	61.5	20.7 hr.	128	79.0	±20	6.1	Ir-metal powder	Thermal column		Half-life in literature is 19 hr. We find 20.7±5 hr.
123	$_{78}$Pt^{196}	26.6	18 hr.	1.1	0.30	±20	26	Pt-metal foil	Pile		
124	$_{78}$Pt^{196}	26.6	3.3 d	4.5	1.20	±20	114	Pt-metal foil	Pile		See Table IV.
125	$_{78}$Pt^{198}	7.2	31 min.	3.92	0.292	±20	9.4	Pt-metal foil	Thermal column		
126	$_{79}$Au^{197}	100	2.7 d	96.4	96.4	±10	19.3	Au-metal foil	Thermal column		A 14 percent correction for conversion electrons has been made.
127	$_{80}$Hg^{204}	6.7	5.5 min.	0.34	0.0228	±20	9.4	HgO powder	Thermal column		
128	$_{80}$Hg^{202,204}		51.5 d		0.725	±20	77	HgO powder	Pile		
129	$_{81}$Tl^{203}	29.1	4.23 min.	0.273	0.079	±20	10	$TlNO_3$	Thermal column		
130	$_{81}$Tl^{205}	70.9	3.5 yr.	3.1	2.2	±20	25.6	$TlNO_3$	Pile		
131	$_{83}$Bi^{209}	100	5.0 d	0.015	0.015	±20	16.0	Bi-metal powder	Pile		

the thermal neutron flux, are as follows: After intercalibrating the standard indium monitors with the standard manganese and copper monitors, the effect on the calculated value of the cross sections was about ±15 percent. The nv determinations from gold-foil pile monitors was only accurate to ±15 percent. This largest source of error was reduced considerably by two other independent nv calibrations (Kubitschek's BF_3 counter and cell and comparison with Fermi's transmission measurements) each of which were accurate to about 3 percent. As a result of these calibrations, all the cross sections measured in the thermal column were reduced by the factor 1.09.

Errors connected with the measurement of N, the number of atoms on the foil, were: The accuracy of weighing on the analytical balance was 0.2 mg, so for the lightest foils of 2.0 mg this leaves an error of ±10 percent, and considerably less on the heavier foils. The error of assay was quite small, less than 0.3 percent.

Errors connected with the measurement of τ, the mean life, arose as follows: In general, no attempt was made to accurately measure the half-life, and the value listed in Seaborg's table of radioactive species was taken. In a few cases the value listed was found to be quite different from the observed half-life. The latter was then used. These are noted under "Remarks" in the tables. An example is 60-day iridium which we followed for 2 half-lives and found 70±2.5 days. The error in half-life is thus probably less than 5 percent unless stated otherwise.

In general the error for any calculated cross section was less than the sum of all the errors listed above. For each cross section listed in Table III the probable error was computed on the basis of the number of trial runs made, the type of radiation detected, the strength of the β-rays, and the presence or absence of gamma-rays. The probable errors are listed as ±10, ±20, or ±40 percent.

3. RESONANCE NEUTRON ACTIVATIONS

The survey of all the slow neutron activities was conducted by irradiating in the thermal column of the graphite pile. But when this did not give sufficient intensity, the substances were irradiated in the center of the pile[7] where the thermal flux was 470 times greater, and, in addition, resonance neutrons from fission energy and below were present. Thus substances which received pile neutron irradiations were activated by resonance neutrons in addition to thermal neutrons. *The exact contribution from resonance activation was unknown, hence, was not subtracted off in the calculation of the thermal cross section.* However, the following will show that the resonance contribution was small for most cases.

Column 9 of Table II indicates that pile irradiations were used mostly[8] for substances with low thermal cross sections. Low thermal cross sections usually indicate a very small value of $\int\sigma(E)dE$, and hence would give very little resonance activation.

Substances prepared for pile irradiation were spread out in a Lusteroid test tube lying flat in the center of the pile. This allowed 95 percent or more transmission in the thermal region, but resonance neutrons would be strongly self-absorbed. The strong resonance absorption is caused by the sharp peaks in the resonance cross-section *vs.* energy curve.[9] Hence, the self-absorption reduces the resonance activation.

The intended program at Argonne included the measurement of $\int\sigma(E)dE/E$ for all activities possible, but because of more urgent experiments, only a few of these values have been obtained so far. Mr. W. Sturm has developed the technique and will report on it independently. The value of $\int\sigma(E)dE/E$ for a few activities was obtained by measuring cadmium ratios, as follows:

$$\frac{\nu_{\text{res}}}{\nu_{\text{thermal}}}=\frac{(q\lambda/\xi)N\int\sigma(E)dE/E}{nv\sigma(v)N}.$$

Now $nv/q=390$ cm from the observed cadmium ratio in the graphite pile with standard indium

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[7] Except that after July, 1944, the thermal column of the Argonne heavy-water pile was used whenever possible.

[8] More explicitly, pile irradiations were used for substances for which σ_{atom}/half-life was quite small, so that a few substances with a very long half-life received pile irradiations in spite of rather large cross section; for example ${}_{27}Co^{59}$ giving rise to a 5.5-year activity with $\sigma=22.5\times10^{-24}$ cm^2.

[9] The 1.4-ev resonance of 54-min. ${}_{49}In^{116}$ has been investigated with a velocity selector by W. W. Havens, Jr. and J. Rainwater, Phys. Rev. **70**, 154 (1946) and has a peak value of $26{,}000\times10^{-24}$ cm^2.

foils. Also for graphite, $\lambda=2.7$ cm and $\xi=0.158$. Using A for activity instead of ν for capture processes.

$$\int \sigma(E)dE/E=22.8(A_{\text{res}}/A_{\text{thermal}})\sigma(v).$$

Since

$$A_{\text{no Cd}}/A_{\text{with Cd}}=(A_{\text{res}}+A_{\text{thermal}})/A_{\text{res}}=\text{C. R.},$$

the desired ratio is then

$$A_{\text{res}}/A_{\text{thermal}}=1/[\text{C. R.}-1].$$

The cadmium ratio (C. R.) is determined by irradiating identical foils, one covered with cadmium, in the center of the pile. The foils were made thin enough to allow a resonance peak of $30{,}000\times10^{-24}$ cm^2. The values of $\int\sigma(E)dE/E$ found are listed in column 11 of Table II.

4. COMPARISON OF ACTIVATION METHOD WITH OTHER METHODS OF MEASURING SLOW NEUTRON CROSS SECTIONS

The other methods of measuring slow neutron cross sections utilize the absorption properties of the total atom, rather than specific isotopes. In a beam geometry the intensity of the beam both with and without the absorbing element is measured by a suitable thermal neutron detector. The general scheme of measuring the reduction of intensity of thermal neutrons by a known weight of the desired absorber can also be applied in a diffusing medium of thermal neutrons, such as paraffin or graphite, and also at the surface of such a medium.[10] Volz[11] utilized a Helmholtz tube filled with radon gas and beryllium to obtain a uniform density of neutrons in water. With the advent of the chain-reacting pile, it has been found possible to measure absorption effects quite accurately by poisoning a few cells with the desired element.[12] Calibration is then made by a similar poisoning with a "black" substance (such as cadmium) of known area. All of the methods which utilize a diffusing medium measure the absorption cross section of the atom, while the beam geometry measures the absorption plus the scattering cross section.

The main differences between measuring the absorption cross section by the absorption and activation methods are:

(1). The absorption method measures the cross section for the whole atom, whereas the activation method measures the cross section for the isotope producing the observed activity. For elements with only one stable isotope, the results should be essentially the same.

(2). The absorption method requires the order of grams to kilograms of material, while the activation method requires the order of milligrams. Volz[11] used from 1 to 4200 grams of the different elements in his survey, while β-ray foils in this survey were from 2 to 200 milligrams.

(3). The absorption method requires the element to be either in pure form or in a compound with other elements whose cross sections are very much smaller. The activation method requires only that the desired induced activity can be separated from the induced activity of all other isotopes present. This property of the activation method allows a wide choice of compounds. For example, it was found possible to measure the cross section of ${}_{11}\text{Na}^{23}$ by using NaCl. However, ${}_{17}\text{Cl}$ has a cross section which is about 50 times greater than ${}_{11}\text{Na}^{23}$, so that this compound could not be used for the absorption method.

(4). When the scattering cross section is of the same order or larger than the absorption cross section, it is not possible to use the beam-absorption method, but the activation method is not even affected by scattering.

5. ACTIVATION CROSS SECTIONS MEASURED

In Table II, the first column lists the isotope, the second column gives the percent natural abundance of this isotope, the third column gives the half-life of the $(A+1)$ isotope (i.e., the isotope produced by neutron capture). Note that the half-life enters into the value of the cross section, and any small change in the accepted value of the half-life would mean a linear change in the cross section value. The cross sections for the isotope and natural atom are given in columns 4 and 5, respectively, and refer to a neutron velocity of 2200 meters per second (one barn equals 10^{-24} cm^2). Note that column 4 is obtained by dividing the value of column 5 by that of column 2. In column 6 is given an estimate of the probable error (see Section 2G). The external absorption coefficient of the β-ray activity, as measured with aluminum absorbers, is given in column 7. Two values are given in column 7 when two distinct groups of β-rays

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[10] J. W. Coltman and M. Goldhaber, Phys. Rev. 69, 411 (1946), measured the capture cross sections of 19 elements in this manner.

[11] Helmut Volz, Zeits. f. Physik 121, 201 (1943) measured the absorption cross section of 49 elements in this manner.

[12] A. Wattenberg has investigated about 50 elements in this manner. See Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. 72, 16 (1947).

could be separated. Column 8 gives the type of foils used and column 9 the place of irradiation, and column 11 gives pertinent remarks. Pile irradiations may result in high cross sections because resonance effects have not been subtracted (see Section 3). An asterisk (*) in column 10 indicates that the production of the radioisotope by thermal neutrons had not been reported in the literature previous to this work.

Table III gives information about certain isotopes decaying by *K*-capture and new properties of isotopes discovered in our survey.

TABLE III. Additional remarks concerning certain isotopes.

Remarks

$_{20}Ca^{40}(n, \gamma)_{20}Ca^{41}$ 8.5 day

The reported $_{20}Ca^{41}$ isotope decays by *K*-capture. An attempt was made to observe the 1.1 Mev γ-ray accompanying each disintegration. The observed activity did not show a fixed half-life but tailed off from 6.1 days to $\gg$8.5 days. Hence, the upper limit of cross section was computed. The last run was made with especially pure $Ca(NO_3)_2$ from which $CaCO_3$ was precipitated out after irradiation. *Note added in proof:* Overstreet and Jacobson, Phys. Rev. **72**, 349 (1947), also fail to find this reported 8.5-day Ca activity.

$_{20}Ca^{48}(n, \gamma)_{20}Ca^{49}$ 30 min., 150 min.

The decay of $_{20}Ca^{49}$ required a somewhat unusual treatment to obtain the cross sections because its isomeric activities of 150-minutes and 30-minutes half-life, both give rise to the same 57-minute half-life daughter, $_{21}Sc^{49}$. This in turn decays to the stable $_{22}Ti^{49}$. Graphs were first drawn from values obtained from the theoretical equations of such relationship in order to study the decay. These were approximate because the equations assumed the initial number of daughter atoms to be zero, whereas they actually were growing and decaying exponentially with the decay of the parent while being irradiated. A general equation was then derived in which the entire activity, without approximations, was extrapolated to include all the growth and decay, during irradiation and afterwards. The cross sections submitted are a result of the application of this equation.

$_{21}Sc^{45}(n, \gamma)_{21}Sc^{46}$ 85 day

The cross section was computed by assuming 95 percent decay by β-rays and 5 percent by *K*-capture, from Walke, *et. al.*, Proc. Roy. Soc. London **A171**, 372 (1939).

$_{24}Cr^{50}(n, \gamma)_{24}Cr^{51}$ 26.5 day

Cross section computed by observing the γ-rays and assuming 0.03γ per disintegration, from Walke, *et. al.*, Phys. Rev. **57**, 171 (1940).

$_{27}Co^{59}(n, \gamma)_{27}Co^{60}$ 10.7 min.

Concerning the 10.7-minute Co^{60}, Livingood and Seaborg[1] suggested that the radiation consisted largely of conversion electrons resulting from an isomeric transition to the longer lived (5.3 year) Co^{60}. Later Nelson, Pool, and Kurbatov[2] claimed that the radiation was that of continuous beta-rays of end point 1.35±0.1 Mev and a γ-ray of 1.5±0.02 Mev but no conversion electrons. Finally, Deutsch and Elliott[3] found that the direct transitions constitute only 10 percent or less of the disintegrations. The β-ray has a maximum energy of 1.50±0.15 Mev and is followed by a γ-ray. At least 90 percent of the disintegrations proceed by an isomeric transition; a 0.056±0.003-Mev γ-ray with corresponding conversion electrons. Our findings are, as a whole, in accord with that of Deutsch and Elliott. We find that 10.8 percent or less of the disintegrations produce a β-ray whose μ/ρ in Al is 12.9 cm^2/g while the rest of the disintegrations (89.2 percent) show up in the form of low energy electrons whose μ/ρ in Al is 147.5 cm^2/g. These low energy electrons must have been produced by a γ-ray of greater than 0.07 Mev in order for our counter to observe them. The cross section has been calculated on the basis of this β-, γ-branching, assuming that each particle (hard or soft) represented a disintegration.

$_{30}Zn^{64}(n, \gamma)_{30}Zn^{65}$ 250 day

Cross section computed assuming 0.6γ per disintegration and 5 percent of disintegration by positron emission. Deutsch, Roberts, and Elliot, Phys. Rev. **61**, 389A (1942).

$_{32}Ge^{70}(n, \gamma)_{32}Ge^{71}$ 11 day

By means of critical absorption in different elements, it was verified that the x-rays observed from 11-d. germanium are actually gallium x-rays, hence come from *K*-capture of 11-d. germanium. From Compton and Allison's book on x-rays, p. 784 and p. 792.

$_{31}Ga$ K_α x-ray line is 1.34A.
$_{32}Ge$ K_α x-ray line is 1.255A.
$_{29}Cu$ *K*-absorption limit is 1.37A.
$_{30}Zn$ *K*-absorption limit is 1.28A.

We observed very marked absorption in copper, but very little absorption in zinc, showing that the x-ray was a Ga K_α-x-ray. Mass-absorption coefficients observed are:

for Scotch Tape (hydrogen, carbon, oxygen)	6.13 cm^2/g
for 13 aluminum	40.8
for 29 copper	165.0
for 30 zinc	57.8

The energy of the Ga K_α-x-ray is only 9.23 kilovolts. No β-rays or electrons were observed. The efficiency of the mica-window Geiger counter for these x-rays was computed by using a value of the mass-absorption coefficient in argon from Compton and Allison, p. 802. The counter was filled with a 10 to 1 mixture of argon-alcohol, but the contribution from the alcohol was negligible.

$_{34}Se^{74}(n, \gamma)_{34}Se^{75}$ 115 day

$_{34}Se^{75}$ has been reported as a *K*-capture isotope with a half-life of 48 days and also of 160 days. We found a *K*-capture activity produced by an (n, γ) reaction on selenium with a half-life of 115±5 days. One sample has been followed for over 180 days. This is the first report of this activity produced by an (n, γ) reaction. To prove that this was a selenium activity, 99.9964 percent pure Hilger Spectroscopic selenium was irradiated in the Argonne pile. From the active material $_{32}Ge$, $_{33}As$, and $_{35}Br$ were separated. No activity was found in any of these fractions. The $_{34}Se$ fraction was then found to contain all the original activity. The *K*-capture decay to stable As^{75} was demonstrated both in the cloud chamber and by x-ray critical absorption edges which show that arsenic *K* x-rays are produced. The arsenic *K* x-rays are more strongly absorbed in gallium than in germanium; while the selenium *K* x-rays would be weakly absorbed in both. Gallium and germanium absorbers were

TABLE III.—*Continued.*

Remarks

prepared and the following mass-absorption coefficients were obtained:

$$\mu/\rho \text{ for } {}_{13}\text{Al}=42\ \text{cm}^2/\text{g},$$
$$\mu/\rho \text{ for } {}_{31}\text{Ga}=102\ \text{cm}^2/\text{g},$$
$$\mu/\rho \text{ for } {}_{32}\text{Ge}=56\ \text{cm}^2/\text{g}.$$

Several γ-rays were found by absorption in lead including an intense one of about 0.4 Mev. The cross section was calculated both on the basis of the cloud-chamber work, an estimation of the counters efficiency for arsenic K x-rays, and on the basis of an estimated efficiency for the γ-rays. The three calculations checked fairly well. A weighted average of these calculations is reported for the cross section. To prove that this activity was that of Se^{75}, arsenic (which consists of only one isotope, As^{75}) was bombarded at the St. Louis cyclotron with 12-Mev deuterons thereby producing Se^{75} by a $(d, 2n)$ reaction. This is the only possible selenium isotope that could be produced which is not stable. The selenium was then separated from the arsenic and the decay of this sample has been followed for a month. It too gives a half-life of 115±10 days. Cf. Friedlander, Seren, and Turkel, Phys. Rev. **72**, 23 (1947).

${}_{38}\text{Sr}^{86}(n,\gamma){}_{38}\text{Sr}^{87*}$ 2.7 hr.

The 2.7-hr. activity of Sr is due to ${}_{38}\text{Sr}^{87*}$, an isomer of the stable isotope. In the past this isotope has easily been produced by fast neutrons on Sr with some indication that the reaction ${}_{38}\text{Sr}^{86}(n, \text{gamma})\text{Sr}^{87*}$ also took place. Stewart, *et al.* (Phys. Rev. **52**, 901 (1937)) produced 2.7-hr. ${}_{38}\text{Sr}^{87*}$ by irradiating Sr inside of a few cm of paraffin with $\text{Li}+D$ neutrons. Although thermal neutrons were present, the few cm of paraffin could not remove all the fast neutrons, so the experiment was not conclusive. H. Reddeman (Naturwiss. **28**, 110 (1940)) showed that the fast neutron activity on Sr was due to the ${}_{38}\text{Sr}^{87}(n, n){}_{38}\text{Sr}^{87*}$ reaction. By irradiating in the same geometry with fast *and slow* neutrons, the 2.7-hr. activity was doubled, thus indicating that the reaction ${}_{38}\text{Sr}^{86}(n,\gamma){}_{38}\text{Sr}^{87*}$ also took place. In the thermal column of the Argonne pile (where the cadmium ratio is >20,000) we irradiated $\text{Sr(NO}_3)_2$ and observed the 2.7-hr. ${}_{38}\text{Sr}^{87*}$ activity. Since no fast neutrons are found in the thermal column, this seems to indicate conclusively that the reaction ${}_{38}\text{Sr}^{86}(n,\gamma){}_{38}\text{Sr}^{87*}$ does take place. The identification of our slow neutron produced activity as Sr^{87*} was made from

(a) the 2.7-hr. half-life,
(b) the shape of the absorption curve which clearly indicated conversion electrons instead of a continuous β-ray spectrum,
(c) the end point of the particles of 0.36 Mev,

all of which agree with the properties of Sr^{87*} listed in Seaborg's tables. Cf. Seren, Engelkemeir, Sturm, Friedlander, and Turkel, Phys. Rev. **71**, 409 (1947).

${}_{41}\text{Cb}^{93}(n,\gamma)$ 6.6 min.

The radio-isotope produced decays either by K-capture or isomeric transition. We are indebted to M. Goldhaber and W. J. Sturm **70**, 111 (1946), who discovered this, and corrected our old erroneous value of the cross section based on Cb^{94} β^- decay.

${}_{50}\text{Sn}^{112}(n,\gamma){}_{50}\text{Sn}^{113}$ 105 day

The indium x-rays produced by the K-capture of ${}_{50}\text{Sn}^{113}$ were detected by taking absorption curves with ${}_{45}$rhodium, ${}_{46}$palladium, and ${}_{47}$silver absorbers. From Compton and Allison's book on x-rays:

For 49 Indium	K-critical absorp λ's
$\lambda K_{\alpha 2}=0.5155\text{A}$	for ${}_{45}$Rh, $\lambda=0.5330\text{A}$
$\lambda K_{\alpha 1}=0.5111\text{A}$	${}_{46}$Pd, $\lambda=0.5080\text{A}$
$\lambda K_{\beta 3}=0.4542\text{A}$	${}_{47}$Ag, $\lambda=0.4845\text{A}$
$\lambda K_{\beta 1}=0.4536\text{A}$	
$\lambda K_{\beta 2}=0.4441\text{A}$	

Note that both the $K_{\alpha 1}$ and $K_{\alpha 2}$ x-ray lines of ${}_{49}$In would be strongly absorbed in ${}_{45}$Rh but not in ${}_{46}$Pd or ${}_{47}$Ag. The $K_{\alpha 1}$ and $K_{\alpha 2}$ comprise 84.3 percent of the x-ray transitions of ${}_{49}$In and the K_β lines the remainder. On the absorption curve, the absorption points taken with ${}_{45}$Rh absorbers fall lower than the ${}_{46}$Pd or ${}_{47}$Ag absorber points due to the presence of In K_α x-rays. The Sn foil was covered first with lucite to remove all the electrons. S. W. Barnes has produced the Sn^{113} isotope by proton bombardment of ${}_{49}$In and finds 2 γ-rays, 0.85 Mev and 0.39 Mev in equilibrium with the 105 day x-rays.

${}_{52}\text{Te}^{130}(n,\gamma){}_{52}\text{Te}^{131}$ 25 min., 30 hr.

Both the 25-min. and 30-hr. periods induced in ${}_{52}\text{Te}^{130}$ by neutron-capture decay into 8.0 day ${}_{53}\text{I}^{131}$. The cross section computed on the basis of the latter activity is almost exactly equal to the cross section computed on the basis of the former two activities, but this is more of a coincidence rather than a demonstration on the accuracy of our measurements. Note that the cross section of all three isotopes ${}_{52}\text{Te}^{126,\,128,\text{ and }130}$ is only 0.287×10^{-24} cm^2 per natural atom.

${}_{62}\text{Sm}(n,\gamma){}_{62}\text{Sm}$ 60 day

No 60-day activity was found. The decay showed a half life of 46 hours for 33 days, and then leveled off into some activity of half-life >3 years.

${}_{63}\text{Eu}(n,\gamma){}_{63}\text{Eu}$ 9.2 hr, 5–8 yr.

The 9.4-hr. ${}_{63}\text{Eu}^{152}$ and 6.5-year ${}_{63}\text{Eu}^{152,154}$ have been found to emit negative particles (Fajans and Steward, Phys. Rev. **56**, 625 (1939)). Hence the mode of disintegration seems to be β-rays, although the possibility of K-capture exists because ${}_{62}\text{Sm}^{152}$ and ${}_{62}\text{Sm}^{154}$ are stable as well as ${}_{64}\text{Gd}^{152}$ and ${}_{64}\text{Gd}^{154}$. The cross sections reported here assume β-ray disintegrations, and K-capture would make the cross sections even larger because the Geiger counter is less sensitive to x-rays than to β-rays. The cross section of long-period Eu was computed assuming that the half-life was 6.5 years, since it is reported from 5 to 8 years.

${}_{73}\text{Ta}(n,\gamma){}_{73}\text{Ta}$ 16.2 min., 117 day

${}_{73}$Ta has only one known stable isotope. A new period of 16.2±0.5 minutes was discovered by irradiating tantalum in the heavy-water pile thermal column. The well known ~100-day ${}_{73}\text{Ta}^{182}$ is also produced by slow neutrons. The new 16.2-minute activity was shown to be tantalum because

(1) Very pure (99.9 percent) tantalum foil gave this activity when irradiated with only slow neutrons.

(2) No other element gives a known 16.2-minute activity with slow neutrons, hence it is unlikely that the observed activity was due to an impurity.

(3) Finally, the element, was confirmed as Ta by chemical separations. A soluble salt, $(\text{NH}_4)_2\text{TaF}_7$, was irradiated in the thermal column and then put into Hf solution. Addition of NH_4OH precipitates the tantalum, which was then washed, redissolved, reprecipitated, and counted. The ratio of short period to long period β-rays was found to be

TABLE III.—*Continued.*

Remarks

the same for

(a) the chemically separated, Ta,
(b) the unseparated $(NH_4)_2TaF_7$ salt,
(c) the Ta metal foil.

This shows that both activities are produced by slow neutron capture of ${}_{73}$Ta. The new 16.2-min. Ta activity may be an isomer of the ~100-day ${}_{73}\text{Ta}^{182}$ activity or it may be produced by an undiscovered stable isotope. The former possibility would require two independent β-ray transitions because the 16.2-min. activity does not show any growth after short irradiation, and the shape of its absorption curve indicates a continuous β-ray spectrum rather than a line of conversion electrons. The β-rays of 16.2-min. Ta have a short range of ~50 mg/cm² Al or ~0.2 Mev., and a γ-ray or x-ray is also present. It is difficult to explain the low energy β-ray for such a short half-life. Tantalum and caesium seem to be strikingly similar in that both have only one stable isotope, give rise to two periods upon slow neutron capture, and the long period has a cross section of the order 1000 times greater than that for the short period.

Concerning the long-period ${}_{73}\text{Ta}^{182}$, we have followed the decay for 2 half-lives and find 117 days ±3 days instead of 97 days which is listed in the tables. Our value of 117±3 days is confirmed by Zumstein, *et al*, Phys. Rev. **63**, 59 (1943). Using this value half-life, a new value of the cross section for *thermal* neutrons was obtained by irradiating in the heavy-water pile thermal column. This value is 40 percent lower than the previously reported value obtained by irradiating in the center of the graphite pile. That the difference was due to *resonance* capture was checked by obtaining the cadmium ratio of 1.6 for the 11 mg/cm² Ta foil.

${}_{77}\text{Ir}^{191}(n, \gamma){}_{77}\text{Ir}^{192}$ 1.5 min., and 70 day

We are indebted to M. Goldhaber, C. O. Muehlhause and S. J. Turkel, Phys. Rev. **71**, 372 (1947), who called to our attention the fact that the 1.5-min. Ir^{192} decays into its 70-day isomeric state.

${}_{78}\text{Pt}^{196}(n, \gamma){}_{78}\text{Pt}^{197}$ 3.3 day

As much as 0.5 barns of the reported natural atom cross section of 1.2 barns may be due to 3.3-day activity of ${}_{79}\text{Au}^{199}$ formed by the decay of ${}_{78}\text{Pt}^{199}$.

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[1] Livingood and Seaborg, Phys. Rev. **60**, 913 (1941).
[2] Nelson, Pool, and Kurbatov, Phys. Rev. **62**, 1 (1942).
[3] Deutsch and Elliott, Phys. Rev. **62**, 559 (1942).