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THE DIFFUSION OF GOLD
IN GAMMA URANIUM

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ABSTRACT

The diffusion coefficient of tracer amounts of gold (Au^{198}) in gamma uranium can be described by an Arrhenius-type equation:

$$D = 4.86 \times 10^{-3} \text{ cm}^2/\text{sec} \exp(-30,400 \text{ cal/mol}/RT).$$

The values of D_0 and the activation energy are close to those for self-diffusion in gamma uranium, indicating that the low activation energy for self-diffusion is due to a general weakness of the lattice rather than to easy compressibility of the uranium atom.

I. INTRODUCTION

This study is an attempt to throw some light on the anomalously low D_0 and activation energy values reported for self-diffusion in gamma uranium.⁽¹⁻⁴⁾

The activation energy for self-diffusion, in the case of the vacancy mechanism, is the sum of the heat of formation of a vacancy, ΔH_1 , and the activation energy for its motion, ΔH_2 . A goodly part of the second of these is energy expended in pushing apart the atoms that surround the path between the diffusing atom and the vacancy, or in compressing the diffusing atom.⁽⁵⁾ By studying the diffusion of a tracer atom with a compressibility different from that of the base metal, it should be possible to see whether the compressibility of the uranium atom, or an internal electronic transition that makes the uranium atom smaller, is responsible for the anomalously low activation energy.

In the case of the ring mechanism, which has been suggested as a possible mechanism of self-diffusion in gamma uranium,^(1,2) the activation energy cannot be split up as above. Nevertheless, since a large part of the activation energy for diffusion by this mechanism is expended in the expansion of the "gate" formed by the atoms between which the diffusing atom must pass and in the compression of the diffusing atom, the present experiment is still meaningful.

The tracer chosen for this study was gold. It has a smaller compressibility than uranium (0.6×10^{-12} cm²/dyne for Au, 0.9×10^{-12} cm²/dyne for U at room temperature), as well as other desirable properties (finite solid solubility in gamma uranium, convenient radio-isotope, etc.).

II. EXPERIMENTAL TECHNIQUES

A. Materials

High-purity uranium was used in this study. The chemical composition of the material is given in Table I. The uranium was swaged to a diameter of 1 cm. Specimens 0.5 to 1 cm thick were cut from this rod, water quenched from 690°C, and annealed at 450°C. The gamma grain size was not measured; it should have been close to that of the material used previously,⁽¹⁾ that is, a diameter ranging from 0.2 to several mm.

Table I

CHEMICAL COMPOSITION OF
URANIUM USED IN THIS STUDY *

Element**	Content ppm. by wt
C	11-13
N	13
O	27
Si	20
Mn	2

*C, N and O analyses courtesy of
Ralph Bane; others, of Joe Goleb.

**All others below limit of spectro-
graphic detection.

Gold, 99.99% pure, irradiated 10 days in the isotope tray of CP-5, was used as the tracer.

B. Preparation of Diffusion Couples

The diffusion couples were prepared in a manner similar to that described earlier.⁽¹⁾ After metallographically polishing one end, the cylindrical sample was electropolished in a phosphoric acid bath. Two such samples were placed on the specimen stand of the sputtering apparatus.^(1,6) The gold wire was wrapped around a tungsten hairpin whose

tip was about $1\frac{1}{2}$ in. above the samples. To cut down contamination of the bell jar, a three-inch diameter, standard wall Pyrex tube was placed around the samples and filament. The samples were cleaned by ionic bombardment in purified argon at a current density of about 1 ma/cm^2 . After the samples were clean (as shown by a deposit of uranium on the glass tube), the gold was evaporated onto them.

C. Diffusion Treatment

The two samples were placed into a tantalum cup with the prepared faces against each other. The tantalum cup was dropped into a quartz tube, which was evacuated, flushed five times with purified argon, flamed and sealed off under a vacuum of 1×10^{-5} mm Hg for the diffusion anneal.

The diffusion anneals were carried out in the furnaces previously described.⁽¹⁾ To start the anneal, the samples were placed directly into a furnace running at temperature; they were water quenched to end the anneal.

D. Sectioning and Analysis

The sectioning was carried out as described previously,⁽¹⁾ except that only 0.04-0.05 in. were removed from the sample radius, and only 10 sections were taken from most samples. After weighing, the sections were dissolved in aqua regia, and the solutions were made up to 2-ml volume. Aliquots of varying size, depending on the specific activity of the sample, were taken, made up to standard height in a gamma-counting tube, and were counted in a well type scintillation counter with a Na I(Tl) crystal. More than 10,000 counts were taken from each section. The gamma activity of the uranium was determined from a solution containing no gold, and was subtracted from the total counting rate whenever it exceeded 1%. When different sections from the same sample were counted more than 2 hours apart, half-life corrections were made.

III. DATA AND RESULTS

A. Data

The data on section weights, concentrations, etc., are given in Tables II to XI. The columns give:

1. section number,
2. weight of the section,

3. weight of the section corrected so that the sum of the weights of five sections equals the difference in the sample weight before and after cutting those sections,
4. the thickness of the section, corrected for thermal expansion so as to represent the section thickness at the temperature of the diffusion anneal (the corrections were made using the density data of Chiotti et al.,)⁽⁷⁾
5. the distance of the center of the section from the original interface (X),
6. the square of the above,
7. total counts per minute in that section,
8. the specific activity of the section (I) in counts per minute per milligram (cpm mg),
9. I corrected for uranium activity.

The data of these tables are shown in the customary log I vs X^2 plots in Figures 1 through 5.

The annealing temperatures, annealing times, diffusion coefficients and micrometer corrections are given in Table XII. The times given are corrected for warming up; a preliminary experiment showed that it took 10 ± 2 minutes to heat the sample to any temperature in the gamma phase. Temperature fluctuations during the run were averaged using formulas similar to Armstrong's⁽⁸⁾ and graphical integration. The given temperatures should be accurate to $\pm 1^\circ$.

B. Treatment of Data

The solution of the diffusion equation for the geometrical arrangement used here is:⁽⁹⁾

$$C = \frac{q}{\sqrt{\pi Dt}} \exp(-X^2/4Dt),$$

where C is the concentration of the tracer in a section, X the distance of the center of this section from the original interface, D the diffusion coefficient, t the annealing time, and q the amount of isotope deposited originally. As in most work with radioactive tracers, it was assumed that $I = kC$, where k is a constant. The constant k was absorbed in q, giving

$$\log_{10} I = \log_{10} k' - X^2/9.212 Dt,$$

where k' is a constant for a given sample. The coefficient D was obtained

Table II

CONCENTRATION-PENETRATION DATA FOR SAMPLE 1A

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0 0167	0 0171	0 00201	0 00100	1 0000 x 10 ⁻⁶	2.56 x 10 ⁶	1.53 x 10 ⁵	
2	0 0295	0.0302	0 00354	0 00378	1 4288 x 10 ⁻⁵	4 42 x 10 ⁶	1.50 x 10 ⁵	
3	0 0255	0.0261	0 00306	0 00708	5 013 x 10 ⁻⁵	3 74 x 10 ⁶	1.47 x 10 ⁵	
4	0.0415	0 0424	0 00497	0 01109	1 2299 x 10 ⁻⁴	5 52 x 10 ⁶	1 33 x 10 ⁵	
5	0.0357	0.0365	0 00428	0 01572	2 471 x 10 ⁻⁴	4.56 x 10 ⁶	1.28 x 10 ⁵	
6	0.1000	0.1008	0 01182	0.02377	5 650 x 10 ⁻⁴	1.016 x 10 ⁷	1.016 x 10 ⁵	
7	0.0592	0.0597	0 00701	0.03318	1.1547 x 10 ⁻³	4.48 x 10 ⁶	7 56 x 10 ⁴	
8	0 0614	0.0619	0.00727	0.04033	1 6265 x 10 ⁻³	3.38 x 10 ⁶	5.51 x 10 ⁴	
9	0.0710	0.0717	0 00842	0.04817	2 320 x 10 ⁻³	2.56 x 10 ⁶	3.61 x 10 ⁴	
10	0 0664	0.0670	0 00786	0.05631	3.171 x 10 ⁻³	1.440 x 10 ⁶	2.17 x 10 ⁴	
11	0.0636	0.0634	0 00744	0.06396	4.091 x 10 ⁻³	8.02 x 10 ⁵	1.261 x 10 ⁴	
12	0.0648	0.0645	0.00757	0.07146	5.106 x 10 ⁻³	4.38 x 10 ⁵	6.76 x 10 ³	
13	0.0892	0.0889	0 01044	0.08047	6.475 x 10 ⁻³	2 60 x 10 ⁵	2.91 x 10 ³	
14	0.0994	0.0991	0 01163	0.09151	8.374 x 10 ⁻³	7.72 x 10 ⁴	7.77 x 10 ²	7.67 x 10 ²
15	0.0837	0.0834	0.00900	0.10222	1 0449 x 10 ⁻²	2.70 x 10 ⁴	3.23 x 10 ²	3.13 x 10 ²

Table III

CONCENTRATION-PENETRATION DATA FOR SAMPLE 1B

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0 0477	0 0499	0 00582	0 00291	8 468 x 10 ⁻⁶	5 68 x 10 ⁶	1.19 x 10 ⁵	
2	0 0752	0 0787	0.00919	0 01042	1 0858 x 10 ⁻⁴	8.12 x 10 ⁶	1.08 x 10 ⁵	
3	0 0669	0 0700	0 00817	0 01909	3 644 x 10 ⁻⁴	6 34 x 10 ⁶	9.48 x 10 ⁴	
4	0 0835	0 0874	0 01020	0 02828	7 998 x 10 ⁻⁴	5.96 x 10 ⁶	7.14 x 10 ⁴	
5	0 0822	0 0861	0 01006	0 03841	1 4753 x 10 ⁻³	4 08 x 10 ⁶	4.97 x 10 ⁴	
6	0.0337	0 0333	0 00389	0 04538	2 059 x 10 ⁻³	1.220 x 10 ⁶	3.62 x 10 ⁴	
7	0 0766	0 0757	0 00883	0 05175	2 678 x 10 ⁻³	1.846 x 10 ⁶	2 41 x 10 ⁴	
8	0 0716	0 0708	0 00826	0.06029	3 635 x 10 ⁻³	1.068 x 10 ⁶	1.492 x 10 ⁴	
9	0 0841	0.0832	0 00971	0.06928	4.800 x 10 ⁻³	6.32 x 10 ⁵	7 52 x 10 ³	
10	0 0769	0.0760	0.00887	0.07857	6 173 x 10 ⁻³	2.60 x 10 ⁵	3.38 x 10 ³	

Table IV

CONCENTRATION-PENETRATION DATA FOR SAMPLE 2A

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0.0070	0.0069	0.00072	0.00036	1.2960×10^{-7}	8.56×10^6	1.223×10^6	
2	0.0261	0.0259	0.00269	0.00206	4.244×10^{-6}	2.52×10^7	9.66×10^5	
3	0.0621	0.0616	0.00638	0.00660	4.356×10^{-5}	5.72×10^7	9.22×10^5	
4	0.0671	0.0666	0.00690	0.01324	1.7530×10^{-4}	5.28×10^7	7.87×10^5	
5	0.0707	0.0701	0.00727	0.02033	4.133×10^{-4}	4.68×10^7	6.62×10^5	
6	0.0203	0.0206	0.00214	0.02503	6.265×10^{-4}	1.040×10^7	5.12×10^5	
7	0.0577	0.0585	0.00607	0.02914	8.491×10^{-4}	2.62×10^7	4.54×10^5	
8	0.0642	0.0650	0.00674	0.03554	1.2631×10^{-3}	2.08×10^7	3.24×10^5	
9	0.0865	0.0876	0.00908	0.04345	1.8879×10^{-3}	1.608×10^7	1.86×10^5	
10	0.0773	0.0783	0.00812	0.05205	2.709×10^{-3}	8.16×10^6	1.055×10^5	
11	0.1212	0.1226	0.01270	0.06246	3.901×10^{-3}	4.38×10^6	3.61×10^4	
12	0.1515	0.1531	0.01587	0.07675	5.891×10^{-3}	1.275×10^6	8.42×10^3	
13	0.0827	0.0836	0.00866	0.08901	7.923×10^{-3}	2.36×10^5	2.85×10^3	
14	0.0546	0.0552	0.00572	0.09620	9.254×10^{-3}	3.62×10^4	6.63×10^2	6.51×10^2

Table V

CONCENTRATION-PENETRATION DATA FOR SAMPLE 2B*

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1- 5	0.0484	0.0483	0.00493	0.01238	4.752×10^{-6}	7.32×10^6	1.901×10^5	
6-10					5.089×10^{-5}		1.780×10^5	
11					1.5326×10^{-4}		1.512×10^5	
12					2.965×10^{-4}		1.419×10^5	
13					5.157×10^{-4}		1.153×10^5	
14					8.638×10^{-4}		8.63×10^4	
15					1.2645×10^{-3}		6.67×10^4	
16					1.6346×10^{-3}		4.53×10^4	

*Since the first ten sections were very thin, they were combined into two sets of five each.

Table VI

CONCENTRATION-PENETRATION DATA FOR SAMPLE 3A

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0 0709	0 0696	0 00817	0 00408	$1\ 6646 \times 10^{-5}$	$2\ 72 \times 10^7$	$3\ 83 \times 10^5$	
2	0 0619	0 0607	0 00713	0 01173	$1\ 3759 \times 10^{-4}$	$2\ 14 \times 10^7$	$3\ 46 \times 10^5$	
3	0 0637	0 0625	0 00734	0 01897	$3\ 599 \times 10^{-4}$	$1\ 680 \times 10^7$	$2\ 64 \times 10^5$	
4	0 0881	0 0864	0 01016	0 02772	$7\ 684 \times 10^{-4}$	$1\ 358 \times 10^7$	$1\ 54 \times 10^5$	
5	0 0897	0 0886	0 01034	0 03797	$1\ 4417 \times 10^{-3}$	$8\ 06 \times 10^6$	$8\ 99 \times 10^4$	
6	0 0517	0 0519	0 00610	0 04619	$2\ 134 \times 10^{-3}$	$2\ 32 \times 10^6$	$4\ 48 \times 10^4$	
7	0 0794	0 0797	0 00936	0 05392	$2\ 907 \times 10^{-3}$	$1\ 598 \times 10^6$	2.01×10^4	
8	0 0647	0 0649	0 00763	0 06242	$3\ 896 \times 10^{-3}$	$5\ 32 \times 10^5$	$8\ 23 \times 10^3$	
9	0 0595	0 0597	0 00702	0.06974	$4\ 864 \times 10^{-3}$	$1\ 788 \times 10^5$	$3\ 00 \times 10^3$	
10	0 0510	0 0512	0 00602	0 07626	$5\ 816 \times 10^{-3}$	$7\ 76 \times 10^4$	$1.522 \times 10^{3*}$	

Table VII

CONCENTRATION-PENETRATION DATA FOR SAMPLE 3B

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0 0479	0 0479	0 00565	0 00282	$7\ 952 \times 10^{-6}$	$1\ 656 \times 10^7$	$3\ 45 \times 10^5$	
2	0 0583	0 0583	0 00687	0 00909	$8\ 263 \times 10^{-5}$	$1\ 854 \times 10^7$	$3\ 18 \times 10^5$	
3	0 0971	0 0971	0 01144	0 01824	$3\ 327 \times 10^{-4}$	$3\ 14 \times 10^7$	$3\ 23 \times 10^{5**}$	
4	0 0402	0 0402	0 00473	0 02632	$6\ 927 \times 10^{-4}$	$6\ 90 \times 10^6$	$1\ 716 \times 10^5$	
5	0 0372	0 0372	0 00438	0 03088	$9\ 536 \times 10^{-4}$	$4\ 80 \times 10^6$	$1\ 290 \times 10^5$	
6	0 0657	0 0662	0 00780	0 03697	$1\ 3668 \times 10^{-3}$	$5\ 72 \times 10^6$	$8\ 71 \times 10^4$	
7	0 0620	0 0624	0 00735	0 04455	$1\ 9847 \times 10^{-3}$	$3\ 12 \times 10^6$	$5\ 03 \times 10^4$	
8	0 0588	0 0592	0 00697	0 05170	$2\ 673 \times 10^{-3}$	$1\ 562 \times 10^6$	$2\ 66 \times 10^4$	
9	0 0668	0 0673	0 00792	0 05915	$3\ 499 \times 10^{-3}$	$8\ 36 \times 10^5$	$1\ 251 \times 10^4$	
10	0 0692	0 0697	0 00821	0 06721	$4\ 517 \times 10^{-3}$	$3\ 36 \times 10^5$	$4\ 86 \times 10^3$	

* Not used in calculating D

** Not used in calculating D Burr from preceding section was included in this section

Table VIII

CONCENTRATION-PENETRATION DATA FOR SAMPLE 4A

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected) counts per minute per milligram)
1	0.0558	0.0557	0.00658	0.00329	1.0824×10^{-5}	7.16×10^6	1.28×10^5	
2	0.0784	0.0783	0.00925	0.01120	1.2544×10^{-4}	8.54×10^6	1.09×10^5	
3	0.0559	0.0558	0.00659	0.01913	3.660×10^{-4}	4.72×10^6	8.45×10^4	
4	0.0597	0.0596	0.00704	0.02594	6.729×10^{-4}	3.32×10^6	5.56×10^4	
5	0.0616	0.0611	0.00722	0.03307	1.0936×10^{-3}	2.02×10^6	3.28×10^4	
6	0.0788	0.0782	0.00924	0.04130	1.7057×10^{-3}	1.244×10^6	1.58×10^4	
7	0.0906	0.0899	0.01062	0.05123	2.625×10^{-3}	6.92×10^5	7.64×10^3	
8	0.0715	0.0709	0.00838	0.06073	3.688×10^{-3}	1.288×10^5	1.80×10^3	
9	0.1170	0.1161	0.01371	0.07178	5.152×10^{-3}	9.64×10^4	8.23×10^2	$8.12 \times 10^2*$
10	0.0945	0.0937	0.01108	0.08417	7.085×10^{-3}	2.56×10^4	2.71×10^2	$2.61 \times 10^2*$

Table IX

CONCENTRATION-PENETRATION DATA FOR SAMPLE 4B

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected) counts per minute per milligram)
1	0.0368	0.0372	0.00438	0.00219	4.796×10^{-6}	3.08×10^6	8.37×10^4	
2	0.0562	0.0568	0.00669	0.00772	5.960×10^{-5}	4.52×10^6	8.05×10^4	
3	0.0666	0.0673	0.00792	0.01503	2.259×10^{-4}	4.60×10^6	6.90×10^4	
4	0.1045	0.1057	0.01243	0.02521	6.355×10^{-4}	4.36×10^6	4.17×10^4	
5	0.0680	0.0688	0.00810	0.03547	1.2581×10^{-3}	1.45×10^6	2.13×10^4	
6	0.0550	0.0549	0.00646	0.04275	1.8276×10^{-3}	5.52×10^5	1.004×10^4	
7	0.0636	0.0635	0.00748	0.04972	2.472×10^{-3}	2.88×10^5	4.53×10^3	
8	0.0615	0.0614	0.00723	0.05708	3.258×10^{-3}	1.080×10^5	1.756×10^3	
9	0.1078	0.1077	0.01268	0.06703	4.493×10^{-3}	4.02×10^4	3.73×10^2	
10	0.0687	0.0686	0.00807	0.07741	5.992×10^{-3}	1.584×10^4	$2.30 \times 10^{2*}$	

* Not used in calculating D

Table X

CONCENTRATION-PENETRATION DATA FOR SAMPLE 5A

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0.0652	0.0655	0.00773	0.00386	1.4900×10^{-5}	4.84×10^7	7.43×10^5	$4.55 \times 10^2*$
2	0.0880	0.0884	0.01043	0.01295	1.6770×10^{-4}	5.34×10^7	6.07×10^5	
3	0.0918	0.0922	0.01088	0.02360	5.570×10^{-4}	3.68×10^7	4.01×10^5	
4	0.0991	0.0995	0.01175	0.03492	1.2194×10^{-3}	1.892×10^7	1.91×10^5	
5	0.0697	0.0700	0.00826	0.04492	2.018×10^{-3}	5.60×10^6	8.04×10^4	
6	0.0580	0.0586	0.00692	0.05251	2.757×10^{-3}	2.16×10^6	3.73×10^4	
7	0.0743	0.0751	0.00886	0.06040	3.648×10^{-3}	9.76×10^5	1.31×10^4	
8	0.0802	0.0810	0.00956	0.06961	4.846×10^{-3}	3.12×10^5	3.89×10^3	
9	0.0787	0.0795	0.00938	0.07908	6.254×10^{-3}	8.92×10^4	1.133×10^3	
10	0.0794	0.0802	0.00946	0.08850	7.832×10^{-3}	3.70×10^4	4.66×10^2	

Table XI

CONCENTRATION-PENETRATION DATA FOR SAMPLE 5B

Section Number	Weight (grams)	Corrected Weight (grams)	Thickness (cm)	X (cm)	X ² (cm ²)	Counts per Minute	I (counts per minute per milligram)	I (corrected counts per minute per milligram)
1	0.0852	0.0848	0.01000	0.00500	2.500×10^{-5}	1.946×10^7	2.28×10^5	8.94×10^2 2.53×10^2 $1.546 \times 10^2*$
2	0.0817	0.0813	0.00959	0.01480	2.190×10^{-4}	1.376×10^7	1.684×10^5	
3	0.0821	0.0817	0.00964	0.02441	5.958×10^{-4}	9.92×10^6	1.208×10^5	
4	0.0827	0.0823	0.00971	0.03409	1.1621×10^{-3}	5.18×10^6	6.27×10^4	
5	0.1067	0.1061	0.01253	0.04520	2.043×10^{-3}	3.16×10^6	2.97×10^4	
6	0.0589	0.0592	0.00698	0.05496	3.021×10^{-3}	8.80×10^5	1.494×10^4	
7	0.1159	0.1164	0.01373	0.06531	4.265×10^{-3}	4.16×10^5	3.59×10^3	
8	0.0604	0.0607	0.00716	0.07576	5.740×10^{-3}	5.46×10^4	9.04×10^2	
9	0.0836	0.0840	0.00991	0.08430	7.106×10^{-3}	2.20×10^4	2.63×10^2	
10	0.0728	0.0732	0.00864	0.09357	8.755×10^{-3}	1.202×10^4	1.651×10^2	

*Not used in calculating D.

27035

Fig. 1. Penetration Plots for Samples 1A and 1B

27034

Fig. 2. Penetration Plots for Samples 2A and 2B

27033

Fig. 3. Penetration Plots for Samples 3A and 3B

27037

Fig. 4. Penetration Plots for Samples 4A and 4B

27032

Fig. 5. Penetration Plots for Samples 5A and 5B

Table XII

DIFFUSION DATA

Sample	Diffusion Temp, °C	Time	D, 10 ⁻⁹ cm ² /sec	D _{corr} *, 10 ⁻⁹ cm ² /sec
1A	784.6	46 hr 30 min	2.47	2.70
1B	784.6	46 hr 30 min	2.61	2.63
2A	843.5	16 hr 50 min	5.38	5.33
2B	843.5	16 hr 50 min	4.92	5.47
3A	911.2	6 hr 30 min	10.8	11.8
3B	911.2	6 hr 30 min	11.4	10.9
4A	949.7	3 hr 7 min	19.7	19.8
4B	949.7	3 hr 7 min	18.4	18.9
5A	1006.8	2 hr 0 min	32.9	31.8
5B**	1006.8	2 hr 0 min	36.6	42.8

$$*D_{\text{corr}} = D \left(\frac{\text{Total thickness removed according to micrometer}}{\text{Total thickness removed according to weight}} \right)^2$$

**Value discarded because large difference between D and D_{corr} indicates an error in sectioning.

from a linear least-squares analysis of $\log_{10} I$ vs. X^2 . The D values thus obtained were corrected so that the total thickness removed equalled the thickness removed as measured by the micrometer.⁽¹⁾

On several penetration plots, the last one or two points deviated upward from the straight line, indicating a small component of fast diffusion, possibly along grain boundaries or dislocations. These points were not used in the calculation of D . The D value from sample 5B was discarded because the large difference between the measurements by micrometer and by weight of the amount of material removed indicates an error in sectioning.

C. Results

The D values are tabulated in Table XII and plotted vs. $1/T$ in Figure 6. Fitting the data to an Arrhenius-type equation:

$$D = D_0 \exp(-Q/RT),$$

one obtains D_0 equal to $(4.86 \pm 1.3) \times 10^{-3} \text{ cm}^2/\text{sec}$ and Q equal to $30,400 \pm 520 \text{ cal/mol}$.

27400

Fig. 6. Arrhenius Plot for Diffusion in Gamma Uranium

D. Errors

The errors were estimated to be as follows: 1% each for counting, weighing, dissolution and pipetting, and 4% due to misalignment in sectioning. The largest difference between two identically annealed samples was 8%, which is not too far outside these limits. The 1° uncertainty in the temperature caused an error of 1.5% in D. The total error was less than 7%.

IV. DISCUSSION

Although the activation energy for the diffusion of gold is significantly greater than that for self-diffusion in uranium, it does not approach the value expected from the usual $Q-T_m$ correlation.⁽¹⁰⁾ In terms of the ideas referred to previously,⁽⁵⁾ it can be said that the low activation energy is not due to ease of compression of the uranium atom or to any internal electronic transitions in the uranium atom. It is possible that the low activation energy for self-diffusion is due to very low elastic constants in the gamma phase of uranium, in agreement with its very low mechanical strength; or to a very low energy of vacancy formation. A more quantitative discussion of this point is not possible because the elastic constants of gamma uranium are not known. For the same reason, quantitative comparison with other theories of diffusion is also difficult. The direction of the change in the activation energy is in agreement with the theory proposed by Lazarus;⁽¹¹⁾ the activation energy for solute diffusion is greater than that for self-diffusion because the valence of the solute is less than the valence of the solvent.

The present data do not throw much light on the mechanism of diffusion in gamma uranium. The diffusion of gold probably takes place by the same mechanism as self-diffusion.

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