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CAPTURE CROSS SECTION OF GOLD AS A FUNCTION OF NEUTRON ENERGY

WORK DONE BY:

- J. M. Blair
- M. Deutsch
- K. I. Greisen
- A. O. Hanson
- G. A. Linenberger
- R. F. Taschek
- C. M. Turner
- J. H. Williams

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REPORT WRITTEN BY:

K. I. Greisen

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ABSTRACT

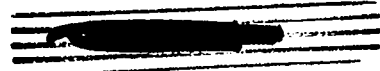
The capture cross section of gold has been measured as a function of neutron energy in the range 30 kv to 3 Mev, by comparing the beta activity induced in a gold foil with the number of fissions in a thin 25 or 28 sample exposed to the same neutron beam. The results are presented in Fig. 3 and Table I.

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CAPTURE CROSS SECTION OF GOLD AS A FUNCTION OF NEUTRON ENERGY

In order to obtain the capture cross section of gold, foils of this material were exposed to fairly monoenergetic beams of neutrons, and the 2.7-day beta activities induced in the foils were subsequently measured. For all exposures except the one at highest energy, the neutron intensity was monitored with an enriched uranium foil, which contained approximately 98.3% of ^{235}U and had a 23-to-25 mass ratio of 3.35. The uranium and gold foils were fastened on opposite sides of a common high-voltage plate of a double ionization chamber, which was placed so that the gold foil was two inches from a lithium target bombarded by protons accelerated by an electrostatic generator. Because of the thickness of the high-voltage plate, the uranium sample was 4.3 percent farther from the target than the gold. The uranium foil was circular with 1-inch diameter, while the gold was rectangular, 0.9 x 1.0 inches in size. Since both foils subtended nearly the same angle at the target (about 14° to each side of 0°), and since the distances differed by only a few percent, the beams striking the two foils might be considered identical.

Through the courtesy of the P-3 Group, the exposure at highest energy was taken with the D(d,n) source, and was monitored with a foil containing 1.71 mg of ordinary uranium on a circle of 1-1/4 inch diameter. In this case the uranium foil was 2-1/2 inches from the target, while the distance to the gold was 1-3/4 inches.

In order to protect the foils from scattered neutrons of thermal energies, the ionization chambers and foils were covered with cadmium. The gold was protected from scattered neutrons of its 5-volt resonance energy by placing additional gold foils, during the exposure, on both sides of the gold for which the activity

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was to be measured. After one exposure at about 300 kev, the activities of these outside foils were measured in addition to that of the middle foil. The activities of the outer foils averaged 5 percent \pm 2 percent higher than that of the middle foil, which indicates the absorption of a small number of neutrons of resonance energy.

The activity of the gold foil was measured with a Geiger counter of the Chicago type, which had walls of dural about 4-1/2 mils thick. In order to have high counting rates, the length of the foil during counting was made approximately equal to the circumference of the counter; i.e., 2-3/4 inches. The thickness of the foil was 5 mils. The foil was cut into three equal parts, 1" x .9" x .005", which were stacked on top of each other during the exposure to the neutron beam in order to make the energy and intensity variation over the foil small. These parts were later fastened end-to-end with scotch tape, so that they formed a cylinder which slipped tightly over the Geiger counter. Counts were taken repeatedly after each exposure, over a period of about 4 days, to make certain that the activity being measured was the 2.7-day activity of gold. No evidence was found for any activity of a different period. For the low counting rates at high energy, the limit of accuracy in counting was about 1/2 count per minute, set by fluctuations in the background rate. For the higher counting rates the chief error was statistical and was of the order of one percent.

In order to calculate the capture cross sections from the Geiger-Müller counting rates, one needs to make a measurement equivalent to measuring the efficiency of the counter. This was done through the courtesy of the P-1 Group, by placing the chamber containing the uranium and gold foils in a large carbon block irradiated by neutrons from a cyclotron. Since the thermal cross section of 25

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and Au are fairly well known, the efficiency could be calculated from the counting rates obtained in this exposure, with the following formula:

$$E = 5630 M_{25} \times \frac{197}{235} \times \frac{R_0}{M_{Au} F} \times \frac{\sigma_{25}}{\sigma_{Au}} \quad (1)$$

Here M_{25} is the mass of the 25 foil; $197/235$ is the ratio of atomic weights of gold and 25; R_0 is the initial counting rate in counts per minute; $5630 R_0/M_{Au}$ is the integrated activity of the gold foil, per unit mass of the foil; F is the number of fissions observed per minute; and σ_{25}/σ_{Au} is the ratio of the thermal fission cross section of 25 to the thermal capture cross section of gold. The quantity E is really the ratio of the efficiency for counting the gold activity to the efficiency for counting the number of fissions in the 25 foil; however, it is this ratio that is needed, rather than the separate efficiencies, for calculating the cross section at the higher energies.

Because the gold foils were somewhat thick for thermal neutrons as well as for the beta particles emitted, the value of R_0/M_{Au} is a function of depth in the gold, and the appropriate value of R_0/M_{Au} for Eq. (1) must be the value at the surface of the gold which is adjacent to the 25 foil. The counting rate observed with any of the foils, however, is indicative of the neutron absorption not at the surface but at an average depth of about one mil. As described above, there were five foils, each of 5-mil thickness, stacked on top of each other during the exposure to the neutrons. Each of these was sufficiently active to be counted separately on the Geiger counter, first with one side of the foil facing the counter and then with the reverse side on the counter. Thus as many as ten points in a sort of neutron absorption curve could be obtained, and from the curve the value of R_0/M_{Au}

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might be picked which was appropriate for the edge of the gold adjacent to the 25 foil. This absorption curve is shown in Fig. 1. The value of R_0/M_{Au} at the surface is taken as 780 ± 10 . The curve is also useful in that it affords a check on the thermal value of the gold capture cross section, and hence on the average energy of the neutrons as well as on the possible existence of neutrons of the gold resonance energy. This check is based on the natural assumption that the absorption cross section σ_a is the same as the capture cross section σ_r , since no other process is anticipated than the radiative capture leading to beta emission. In Fig. 1 the points are the experimental values of R_0/M_{Au} while the solid curve is the absorption curve calculated on the assumptions that $\sigma_a(Au) = 94$ barns and that the thermal neutron intensity is distributed according to $1 + 1/2 \cos^2 \theta$ incident on one face and $1 - 1/2 \cos^2 \theta$ incident on the reverse face, θ being the angle between the normal to the face and the direction of motion of the neutrons. Since no good fit could be obtained, regardless of the angular distribution assumed, with $\sigma_a(Au)$ different by more than 10 barns from 94, which is the accepted thermal cross section, we may conclude that there were not many resonance neutrons present and that the neutrons were well thermalized.

In the thermal exposure described above, the number of fissions recorded was 4.49×10^4 . A small correction is needed in this number because of the imperfect shadowing of the uranium foil by the gold foils. A geometrical calculation shows that if the foils had been infinite in extent, the value of F would have been smaller by about two percent; hence we take $F = 4.40 \times 10^4$.

For the thermal capture cross section of gold we have taken 94 barns, and for the thermal fission cross section of 25 we have used 552 barns, which has been obtained by using the value 0.16 for α (the ratio of capture to fission cross

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sections in 25), and taking the total cross section as 640. From Eq. (1) and these numerical values, we obtain the efficiency ratio

$$E = 4.83 \times 10^{-2}.$$

The capture cross section of gold at the higher energies may be calculated with the following formula:

$$\sigma_r(\text{Au}) = \frac{5630}{E} \frac{R_0}{M_{\text{AuF}}} \times \frac{d^2(\text{Au})}{d^2(25)} \times 197 \sum_s \left(\frac{M_s \sigma_f(s)}{A_s} \right) \quad (2)$$

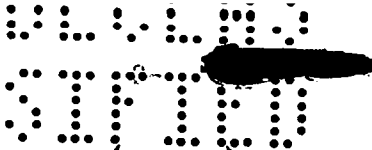
Here E is the efficiency obtained above, R_0 and F refer to measurements made at the higher energy, $d(\text{Au})$ and $d(25)$ are the distances from the neutron source to the gold and 25 foils respectively, and M_s , $\sigma_f(s)$, A_s are the mass, fission cross section and atomic weight of the various components s of the uranium foil, over which a summation must be made. Since most of the exposures were made at energies below the 28 threshold and were monitored with the same foil as that used for the thermal exposure, we find that $\sigma_r(\text{Au})$ is independent of several of the quantities which enter into both Eq. (1) and (2). In fact, for energies below the 28 threshold, these equations may be combined to give

$$\left(\frac{\sigma_r(\text{Au})}{\sigma_f(25)} \right)^{(E)} = \left(\frac{\sigma_r(\text{Au})}{\sigma_f(25)} \right)^{(\theta)} \left(\frac{F_{\text{MAu}}}{R_0} \right)^{(\theta)} \left(\frac{R_0}{M_{\text{AuF}}} \right)^{(E)} \frac{d^2(\text{Au})}{d^2(25)} \quad (3)$$

where the superscript θ refers to thermal energy, and E to any energy below the 28 threshold. For energies E above the 28 threshold, the right-hand side of this equation must be multiplied by the quantity

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$$\frac{235}{M_{25}\sigma_{25}} \sum \left(\frac{M_s \sigma_f(s)}{A_s} \right)$$

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which below the 28 threshold is equal to 1.

In Table I we list the data taken in the exposures at higher energy and the values of $\sigma_f(\text{Au})$ calculated at these energies by use of Eq. (3). The values of $\sigma_f(25)$ listed in this table were derived by using the absolute value 1.33 barns obtained at 1 Mev by Koontz and Rossi, together with the relative values at different neutron energies which have been obtained by Hanson using the "Long Counter" as a neutron monitor. The value of $\sigma_f(28)$ at 3 Mev was measured by Agnew in the P-3 Group, for the same neutron beam as that used in the exposure of the gold foil. The value of $\sigma_f(26)$ at 1730 kilovolts has been derived from the value given in the L.A. Handbook, LA-11, by applying the same correcting factor as is needed to bring the value of $\sigma_f(25)$ at 1 Mev into agreement with the more recent measurement by Koontz and Rossi.

The calculation of the cross section for the 30 kv exposure required a slight correction because of the fact that during part of the exposure, at least, the neutron beam struck only the central part of the foils. This low energy exposure was obtained by setting the proton energy in the Van de Graeff generator slightly below the threshold for the $\text{Li}(p,n)$ reaction, and allowing the small fluctuations in energy to produce neutrons almost exactly at threshold. In this case the neutron beam occupied a cone of small angle. If the cone did not include the entire foils, the ratio of areas of uranium and gold included in the beam would be as the squares of the distances to the target, or 1.087, whereas for the exposures at higher energies the total areas were included and the ratio was 0.857. This indicates a correction for the 30 kv exposure by a factor of $1.087/0.857$ or



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1.27. However, the fluctuations in proton energy were occasionally large enough so that the neutron beam occupied a cone which included the entire foils. Hence the correcting factor lies between 1 and 1.27, and we have chosen 1.15, which is not in error by more than 10 percent.

The results obtained as described above, and listed in Table I, have been plotted as circles in Fig. 3, which shows the capture cross section of gold as a function of neutron energy. It may be noted that for energies above about 160 kv the data are representable on a logarithmic graph by a straight line of slope -0.89, indicating that in this region $\sigma_p(\text{Au})$ is proportional to $(\text{energy})^{-0.89}$.

The last row in Table I and the point indicated by a square in Fig. 3 are the results of an independent measurement which was made in order to study the cause of a discrepancy which appears to exist between these measurements of $\sigma_p(\text{Au})$ and others which had been made at about 200 kev by Hanson and by Linenberger. The method was the same as that described above, except that a different uranium foil, ionization chamber and recording outfit were used for monitoring the exposure, the apparatus used being that of Linenberger. He exposed simultaneously a thin gold foil for himself and a set of thick foils for us, in identical geometry. Two exposures were required, one with a primary neutron energy of 200 kilovolts (obtained in Group P-2 with the Van de Graaff generator) and one with thermal neutrons (obtained in Group P-1 with the carbon pile and cyclotron). The beta counting for his thin foil and for our thick foils was then done on separate Geiger-Müller counting outfits. The purpose of the test was to check on the accuracy of the beta-counting technique, and to see whether the differences between the earlier measurements arose from the beta counting or from the exposing and fission counting. The efficiency ratio E , calculated from the thermal exposure with the thick foils,

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was 5.39×10^{-2} which is about 12 percent higher than the value 4.83×10^{-2} obtained from the earlier exposure. The value of $\sigma_p(\text{Au})$ derived at 200 kv was 0.40 barns, which is about 25 percent lower than the value 0.52 barns obtained from the graph of the earlier results. The absorption curve obtained from the thermal exposure is shown in Fig. 2.

The value of $\sigma_p(\text{Au})$ at 200 kv found by Linenberger, from the beta-counting of the thin foils exposed simultaneously with our thick foils, was 0.43 barns (indicated in Fig. 3 with a vertical cross), which is only about 7 percent higher than our value of 0.40 barns. By a completely independent method, which does not involve beta counting, Hanson has found $\sigma_p(\text{Au}) = 0.415$ barns for Y-Be neutrons, the average energy of which was also about 200 kilovolts. This value is indicated in Fig. 3 by a diagonal cross. The good agreement between these three values of $\sigma_p(\text{Au})$ at 200 kilovolts indicates that the correct value is probably not far from 0.415 barns, and that the results indicated by circles in Fig. 3 are probably too high.

Some of the sources of error in this experiment may be listed as follows:

1) The energy ascribed to the neutrons for the various exposures may be in error. Actually there was a considerable spread in energy for the lower-energy exposures, because the Li target used in the Van de Graaff generator had the thickness equivalent to 70 kev proton energy. The only exception to this was the exposure at 200 kev, for which the target thickness was about 10 kev. In particular, the 30 kev exposure is subject to error because the neutron energy changes very rapidly with proton energy just at threshold. The energies listed in Table I and used in plotting Fig. 3 were the approximate mean energies of the neutrons. Of course, if there is an error in the energy, there is also a consequent error in the fission cross section chosen for the calculation of $\sigma_p(\text{Au})$, and the two errors partly cancel each other.

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2) Statistical errors. At no energy was the combined statistical error greater than 5 percent.

3) There may be errors in the fission cross sections used. In particular, this affects the comparison between our results and those of Hanson, which did not depend on the fission cross section but were a direct measure of the absorption in gold.

4) The efficiency of the counter may have changed with time and with counting rate. We have no positive evidence for the change with time, but we observed that when the counting rate was increased, it was necessary to raise the counter voltage in order to maintain the same efficiency. This affects particularly the efficiency determination, because the counting rates for the thermal exposures were much higher than for the other exposures.

5) The masses of 25 and 28 in the monitor foils may have been incorrectly determined. However, because the same foil was used for the thermal and higher energy exposures, the mass cancels out except for the exposures at energies above the 28 threshold. Hence errors in the mass can only affect the results above 1 Mev. As a consequence of these sources of error, the absolute values of $\sigma_r(\text{Au})$ obtained in this experiment should be expected to have an uncertainty of about ± 20 percent. The relative values at different energies, however, at least for energies above 100 kev, have an uncertainty of only about half the above error, or ± 10 percent.

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TABLE I

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Mean Energy of Neutrons (kev)	F	R ₀	M _{Au} (grams)	Cross Sections Assumed (barns)	$\frac{A_{25}}{M_{25}} \sum \frac{M_s \sigma_f(s)}{A_s}$ (barns)	$\sigma_f(\text{Au})$ (barns)
30	1161	202	4.325	$\sigma_f(25) = 3.42$	3.42	1.40
160	1060	143	4.31	$\sigma_f(25) = 2.23$	2.23	0.62
380	1720	162	4.33	$\sigma_f(25) = 1.56$	1.56	0.30
750	2285	131	4.27	$\sigma_f(25) = 1.34$	1.34	0.159
1730	3414	59	4.31	$\sigma_f(25) = 1.31$ $\sigma_f(28) = 0.355$	2.49	0.088
3000	3322	17	4.275	$\sigma_f(25) = 1.3$ $\sigma_f(28) = 0.50$	8.7	0.049
300	2048	153	3.09	$\sigma_f(25) = 2.03$	2.03	0.40

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F = number of fissions per minute observed in monitor, R₀ = initial activity of gold foil, expressed in counts per minute, M_{Au} = mass of gold foil. The data in the last row are from an exposure monitored by Linenberger with a different foil from that used in the other exposures; hence a different thermal calibration was used in calculating the last value of $\sigma_f(\text{Au})$.

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Fig. 1
R₀/M₀ vs depth curve for gold foil for
Exposure A taken in carbon black

R₀/M₀ = initial fading rate of gold foil
per unit mass of foil

Solid curve is calculated as assumption of
uniformity of distribution of
from left-hand side, and curve from right
hand side, and taking $\frac{1}{2}(R_0/M_0) = 7.9$ units



Open circles indicate points measured
from surface of foil

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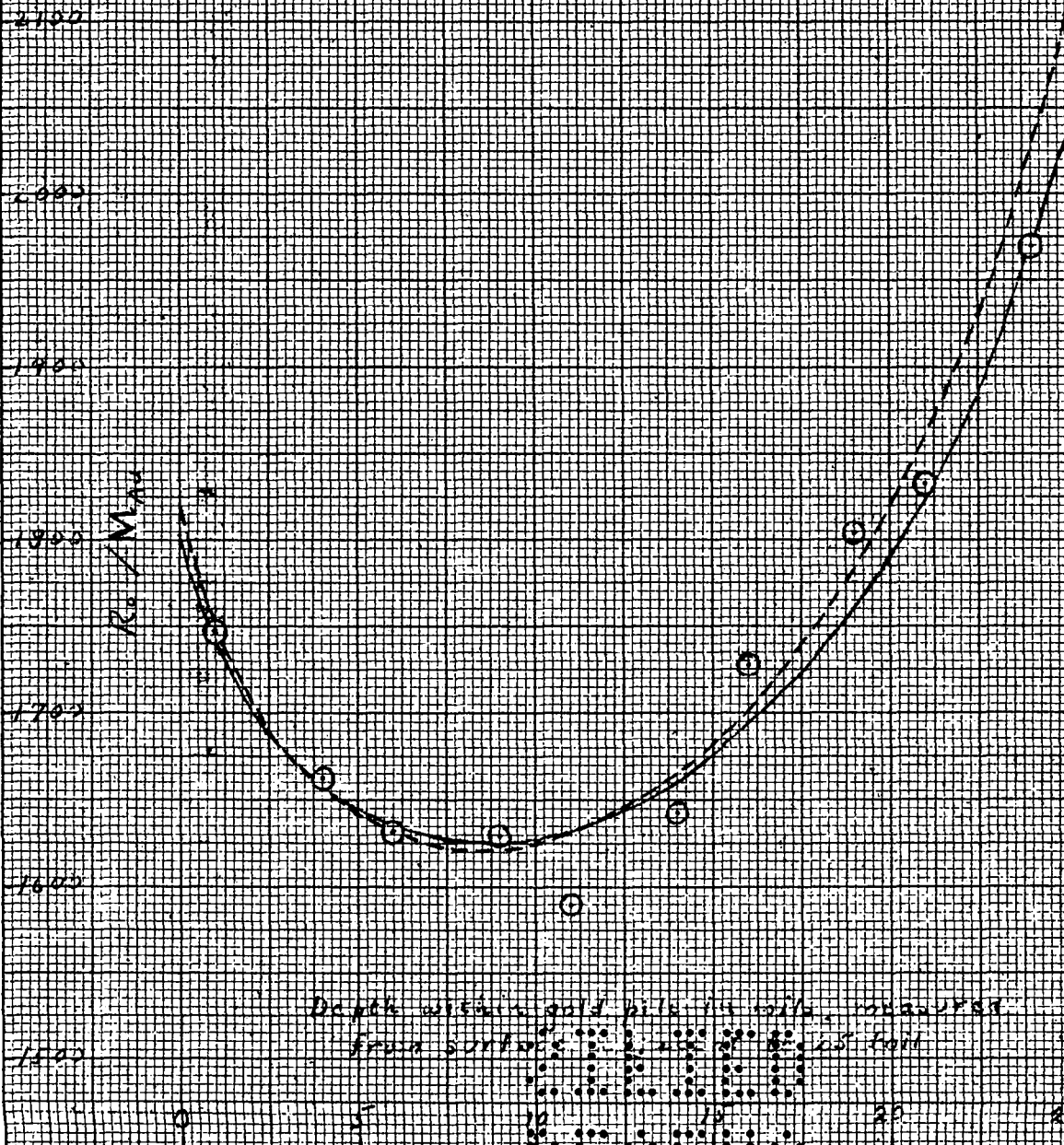
FIGURE 11
 R_0/M_{max} vs. Depth within gold pile in miles measured from surface of gold foil
 Exposure of Target to Radiation

R_0/M_{max} = Initial counting rate of gold foils
 AU per 1.6 cm² of foil.

Solid Curve is calculated on assumption of
 normal velocity distribution before
 year 1945 (west side, 17 east from
 west-hand side)

Dashed Curve is calculated on assumption of
 distribution 1-10 to 100 ft west
 side, 100 to 1000 ft east-hand side.

Both curves calculated with $\sigma_0(R_0) = 74$ errors

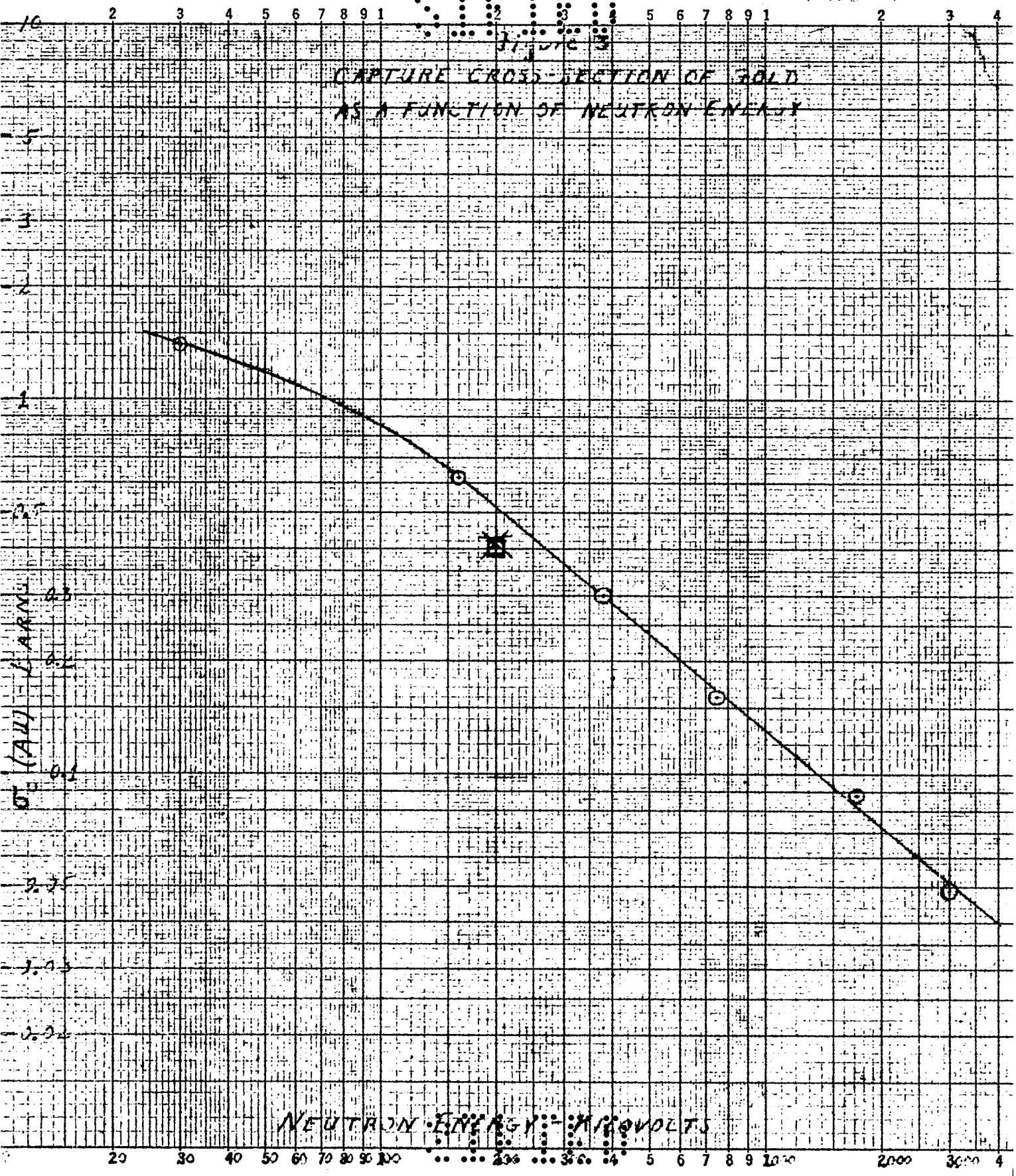


Depth within gold pile in miles measured
 from surface of gold foil

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