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ACTIVATION CROSS SECTIONS BY BORON ABSORPTION*

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ABSTRACT

Using a beam of neutrons from the heavy-water pile and inserting increasing thicknesses of boron absorbers enriched in B^{10}, the activation cross sections of various elements in the range 10-20,000 ev has been studied. Resonances were observed for sodium, aluminum, chlorine, vanadium, manganese, and copper. It is indicated that these resonances show scattering which predominates over absorption. In the case of manganese a strong level at 260 ev is observed, whose properties can be correlated in a reasonable way with the thermal cross sections of manganese by the use of the Breit-Wigner one-level formula.

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INTRODUCTION

The measurement of neutron activation cross-sections in the energy region 10 to 20,000 ev is rendered difficult by the absence of strong sources of neutrons of well-defined energy in this region. One method which has been used for attacking this problem is the employment of beams of neutrons from the pile, filtered by passage through boron. Measurements of fission cross-sections, using filters of thicknesses up to 4 gm/cm^2 normal boron, were made by Fermi and Anderson, CF-2161. Various activation measurements using the same filters have been reported by Lichtenberger, CP-2081, CP-2436, CP-2638, CP-3195.*

The equilibrium spectrum of neutrons escaping from a pile contains:

(a) A strong component of approximately Maxwellian neutrons at a "temperature" somewhat higher than room temperature.

(b) A spectrum of faster neutrons which, under rather general assumptions, will theoretically follow a (dE/E) distribution law up to energies comparable with fission energies.

(c) A spectrum of very fast neutrons which have made only a few collisions since emission from the source and which increase the number of high-energy neutrons above the number to be expected from the (dE/E) law.

Component (a) may be removed by filtering through cadmium. If now a certain thickness of boron, B atoms/cm^2, is introduced into the beam, then the spectrum of type (b) neutrons is altered to:

$$\frac{dE}{E}\, e^{-B\sigma_s(B)}\, e^{-B\sigma_a(B)} \qquad (1)$$

* Metallurgical Project reports.

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where $\sigma_s(B)$ and $\sigma_a(B)$ are the scattering and absorption cross sections of boron at energy E. Assuming, for the moment, that $\sigma_a(B) = k/\sqrt{E}$ and that $\sigma_s(B)$ is constant, then the response of a 1/v detector would be proportional to:

$$(2) \qquad e^{-B\sigma_s(B)} \int_{E_c} \frac{dE}{E^{3/2}} e^{-Bk/\sqrt{E}} \qquad (2)$$

Here E_c is the cadmium cut-off energy. The upper limit should be an energy in the neighborhood of fission energies, but can be taken as infinite for the following applications. Then equation (2) becomes:

$$(3) \qquad e^{-B\sigma_s(B)} \left(\frac{2}{Bk}\right)\left(1 - e^{-Bk/\sqrt{E_c}}\right) \qquad (3)$$

For not too small values of B (sufficiently large so that boron absorption is virtually total at E_c) this reduces to:

$$(4) \qquad e^{-B\sigma_s(B)} \left(\frac{2}{Bk}\right) \qquad (4)$$

Thus for a 1/v detector, the response, multiplied by B, should fall off exponentially with increasing B.

This discussion neglects the contribution of type (c) neutrons. For an unfiltered beam, the relative effect of such neutrons on a 1/v absorber is quite negligible. For thick filters, however, this will not be the case. In the previous experiments referred to above, in order to obtain information about cross sections in the neighborhood of 20 kev, it was necessary to introduce filters so thick that the depletion of the beam due to scattering, $e^{-B\sigma_s(B)}$, was very marked, of the order 1/50. Now, the value of $\sigma_s(B)$ is not known with great accuracy, particularly as a function of energy, and the assumption that it is constant is certainly only a first approximation. In particular,

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one may be fairly certain that the component (c) is simultaneously reduced by much less than a factor 30, because of the expected decrease of scattering cross section at high energy. This means, the response will fall off less rapidly at large B than predicted by (3), and that the use of (3) to determine the cross section of the detector will introduce large errors. This was demonstrated by the appearance of very anomalous apparent cross sections at large B in the previous experiments.

Several measures are introduced to overcome this difficulty, of which the two principal ones are the following:

The experiment is set up to use a beam of neutrons from the heavy-water pile with a collimator so built that the target "sees" none of the uranium metal. Neutrons reaching the target have made, on the average, a considerable number of collisions since being emitted in fission. This arrangement should minimize the number of type (c) neutrons present.

More important still is the use of enriched boron discs to reduce the depletion of the beam by scattering. As described by the manufacturer, the discs were prepared as follows. Fine-grain lead powder and crystalline boron powder [redacted] were mixed together in a batch mixer in the quantities of 28.7% by weight of boron and 71.3 % by weight of lead. [redacted]

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From this mixture, six compacts were prepared in the form of discs 3.90 cm in radius. The discs are described in detail in

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Table 1. By combining discs, we obtained boron thicknesses up to 3.04 g/cm^2 (B^{10}). (See Table 1.) Table 1

The scattering cross section of the compact material per B^{10} atom was determined for thermal neutrons in the 90° scattering apparatus described in CP-2081.* A description of this apparatus will be included in the Plutonium Project Record of the Manhattan Project Technical Series. The mean of several measurements on disc 4 gave σ_s = 4.9b per B^{10} atom.

With this value of σ_s per B^{10} atom, and because of the high concentration of B^{10} in these discs, the depletion of the beam due to scattering never amounts to more than about a factor 2. Thus the error due to possible variation with energy in the value of σ_s is not important, and the relative contribution of type (c) neutrons is greatly reduced as compared to the previous measurements. 1½

EXPERIMENTAL OBSERVATIONS

(1) Table 2 summarizes the significant properties of the targets which were studied. The foils were in the form of thin discs, 2.54 cm in diameter, encased in scotch tape. Decay curves were run in each case to guarantee the purity of the activity being investigated. The results are summarized in Table 3. The first measurement in each case is for an open beam. Then, a Cd filter of thickness 0.172 g/cm^2 was introduced. Finally, increasing thicknesses of B filters were used. The thinnest, of thicknesses 0.442, .0894 g/cm^2, were discs containing ordinary boron. Table 2 Table 3

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* Metallurgical Project Report.

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Table I.

Description of Lead-Boron Discs.

Atomic ratio: 1 B^{10} : 0.20 B^{11} : 0.15 Pb

Compact No.	Actual Weight, (gm)	Range of Thickness	Nominal gm/cm^2 B^{10}	Equivalent* gm/cm^2 B^{10}	Scattering Correction*
176 (1)	36.7	.071" - .077"	.1746	.1479	.957
176 (2)	39.0	.073" - .078"	.1846	.1569	.955
176 (3)	78.0	.146" - .151"	.3716	.3149	.912
176 (4)	77.7	.147" - .152"	.3696	.3131	.912
176 (5)	157.2	.296" - .300"	.7497	.6353	.824
176 (6)	314.3	.595" - .599"	1.4972	1.267	.689

*For discussion of the last two columns, see Section on comparison of normal and enriched boron discs.

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TABLE 2.

Target	Chemical Form	Thickness g/cm^2	σ_a (2200)	Half-life
Na^{23}	NaF	.151	0.4b	14.8h
Al^{27}	Al	.078	0.23	2.4m
Cl^{37}	C_2Cl_6	.173	0.15	37 m
V^{51}	V_2O_5	.186	5.0	3.9m
Mn^{55}	MnO_2	.124	11.5	2.6h
Cu^{65}	Cu	.053	0.6	5.3m
Cb^{93}	Cb_2O_5	.207	0.01	6.6m

(The thickness is given in gm/cm^2 of normal element. The activation cross section is the value for the normal element at 2200 m/sec; it is obtained from the Project Handbook. The cross sections listed there were derived principally from the work of Seren et al. as reported in Physical Review, 71, 463 (1947).

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COMPARISON OF NORMAL AND ENRICHED BORON DISCS

(1) The points for small boron thicknesses were taken with discs containing ordinary boron.

Discs denoted by B_{11}, B_{23}, etc., were prepared at Los Alamos Laboratory, as a lead borate glass. The analyses are those supplied to us by the manufacturers, and are given in Table 4. Table 4

The scattering cross section of the discs per B^{10} atom was determined in the 90° scattering apparatus referred to above for several of the B_{11} discs. The value obtained was σ_s = 3.9b per normal boron atom, or σ_s = 23.6b per B^{10} atom.

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TABLE 3.

Saturated Activities - CPM [c/m] Over Background (20 c/m)

Discs	gm/cm^2 B^{10}	Na	Al	Cl	V	Mn	Cu	Cb
-	0:Ne Cd	1.17×10^{6}	7.22×10^{5}	4.12×10^{5}	4.57×10^{6}	8.41×10^{6}	5.70×10^{5}	9.22×10^{3}
-	0:Cd	3.34×10^{4}	2.26×10^{4}	1.10×10^{4}	1.19×10^{5}	4.18×10^{5}	2.90×10^{4}	1.31×10^{3}
B/1n	.0442	1.47	9.06×10^{3}	3.99×10^{3}	4.67×10^{4}	2.61	1.79	9.36×10^{2}
B/2n	.0894	9.86×10^{3}	6.03	2.21	2.84	1.93	1.35	7.74
(1)	.1479	8.55	4.82	1.83	2.43	1.82	1.29	8.51
(3)	.3149	5.48						
(1)+(2)	.3049		3.28	1.04	1.61	1.19	9.17×10^{3}	6.39
(1)+(3)	.4628	4.42						
(2)+(3)	.4719		2.74	7.13×10^{2}	1.22	7.62×10^{4}	6.43	4.35
(3)+(4)	.6281	3.62	2.43	6.04	1.00	5.57	5.18	3.74
(1)+(5)	.7833	3.05	2.10	5.20	8.62×10^{3}	3.85	4.11	3.12
(1)+(2)+(5)								
(4)+(5)	.9402	2.44	1.96	3.98	7.50	2.68	3.63	2.47
(6)	1.267	1.83	1.46	2.97	5.48	1.43	2.51	1.62
(3)+(6)	1.585	1.10	1.26	2.31	3.88	7.60×10^{3}	1.78	1.28
(5)+(6)	1.904		1.06	1.90	3.06	4.86	1.08	9.87×10^{1}
(1)+(5)+(6)	2.052	7.35×10^{2}						
(3)+(5)+(6)	2.217		8.35×10^{2}		2.27	3.16	1.04	6.98
(3)+(4)+(5)+(6)	2.532	6.36	8.19	1.22	1.68	2.12	7.14×10^{2}	5.06

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TABLE 4.

Normal Boron Absorbers.

Disc	Total Weight, gm	Area, cm²	B, gm/cm²	Pb, gm/cm²	S, gm/cm²	All Others, gm/cm²	B^{10}, gm/cm²	Scattering Correction
B/1n	15.18	39.61	.260	.073	.048	.002	.0442	B/1n .945
B/2n	30.61	"	.525	.147	.097	.005	.0894	B/2n .892
B/3n	65.89	"	1.127	.317	.208	.011	.1915	B/3n .760
B/4n	121.77	"	2.083	.586	.385	.021	.354	B/4n .589
B/5n	242.93	"	4.155	1.168	.768	.042	.705	B/5n .345
B/6n	484.46	"	8.256	2.635	1.532	.084	1.403	B/6n .121

TABLE 5.

Target	Abundance	Resonance Energy (ev)	Resonance Fraction of Epi-Cd Act.	Fraction in (1/v) Comp.	α	ϕ_{th}/ϕ_o	$\sigma \frac{dE}{E}$ x10^{-24} cm²	$\int \sigma \frac{dE}{E}$ res x10^{-24} cm²
Na^{23}	1.00	1710	.192	.608	.238	29.4	.265	.0510
Al^{27}	1.00	9100	.137	.863	.159	25.1	.143	.0195
Cl^{37}	.246	1800	.073	.927	.079	27.4	.0866	.00635
V^{51}	1.00	3370	.118	.882	.134	28.6	3.04	.358
Mn^{55}	1.00	261	.563*	.430	1.327	31.0	14.31	8.16
Cu^{65}	.30	570	.441*	.517	.933	25.2	.621	.299
Cb^{93}	1.00	(136??) (3590?)	(.465) (.382)	.153	5.52	28.0	.0349	(.0163) (.0133)

Ave. 27.8 ± 5%

*Higher resonances present

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As a point of subsidiary interest, not bearing directly on this experiment, we can use the two measurements of scattering cross section (normal and enriched) to obtain separately the scattering cross sections of B^{10} and B^{11} for thermal neutrons. Taking account of the small contributions of the lead and sulphur and solving the resulting simultaneous equations, we get

$$\sigma_s(B^{10}) = 2.6b$$
$$\sigma_s(B^{11}) = 4.0b$$

There is, however, some uncertainty in these figures because of the suspected error in the isotopic constitution of the enriched boron, as discussed below.

As an inter-calibration of the normal discs with the enriched boron discs, the activity of thin U foils (23-minute activity) was measured as a function of nominal B^{10} thickness for the two sets. Figure 1 shows the resulting saturated activities. These activities have been corrected to the values they would have had if there had been no scattering; for this correction, the scattering cross sections per B^{10} atom determined above have been used.

If the isotopic and chemical analyses had been free from error in each case, the two curves would have been coincident. There was evidently an error in one set or the other, as is indicated by the fact that the curves are separated by about a constant ratio of 1.18 in abscissa. Because of other evidence, we have taken this to mean that there was 18% less B^{10} in the enriched discs than claimed, giving the column "equivalent" B^{10} gm/cm^2 of Table 1. If we judged correctly

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in assigning the error to the enriched discs, then our final results are correct as presented, but if instead the normal discs were incorrectly assayed, there will be a slight systematic error in our derived cross sections. The use of other independently produced boron absorbers will serve to settle this point.

ANALYSIS OF BORON ABSORPTION DATA --LIGHT ELEMENTS

We consider in this section the analysis of the results for all the elements studied except uranium. The problem is to deduce a variation of cross section with energy which will account for the data obtained. It is clear, however, that this type of experiment cannot uniquely determine the cross section as a function of energy, since one is not dealing with a monokinetic source. Therefore, the results of the analysis will have to be judged to a considerable extent on the basis of their plausibility.

Let us consider the case of sodium, curves for which appear in Figure 3. The heavy points are the experimental measurements given on Table 3 but corrected for scattering according to Tables 4 and 1. These points may be compared with the dashed curve, which is, except for normalization, the following function:

$$F(B) = \frac{1 - e^{-61.4B}}{61.4B} \qquad (5)$$

According to (3), F (B) is the form the activation curve would take if the detector were a (1/v) detector. It is here normalized to one for B = 0. The cross section of normal boron is assumed to be given by

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$k/\sqrt{E}$ and to be equal to 700×10^{-24} cm^2 at 2200 m/sec; the value of k is therefore 36.3 if B is the thickness in gm/cm^2 of B^{10}. A plot of F(B) is given in Figure 2.

Study of the curve shows that, while at small thickness sodium behaves like a (1/v) detector, the deviation from (1/v) behavior becomes very marked as B increases. By subtracting from the observed points an appropriate amount of (1/v) component, — namely, 80.8% of the unfiltered activity, — the portion of activity remaining takes the form of a straight line on the semi-log plot. This residue is given by the crosses, and the solid curve is a straight line through the points.

A straight line in boron absorption indicates a monokinetic component, or resonance. Now, as mentioned before, one cannot determine uniquely by this method the variation of detector cross section with energy; a number of hypothetical cross-section curves could be concocted which would fit the data reasonably well. But the simplicity and naturalness of the above interpretation leads us to believe that sodium's activation is to be understood in terms of a strong (1/v) component plus a resonance at rather high energy. The slope shown corresponds to an energy of 1720 ev.

This method of procedure determines with some precision the relative amount of (1/v) component present. If the fraction 80.8% had been changed by an appreciable amount, the curve given by the crosses would have deviated strongly from a straight line in the first 0.1 gm/cm^2 of B^{10}. An estimated uncertainty of 5% is to be attached to the fraction representing the amount of (1/v) component at zero boron.

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The statistical weight of the points given by the crosses is lowest at both ends; at the right end because of the reduced counting rates, and at the left end because small differences of large numbers are involved.

Figures (4) to (9) show the resonance activation of the other light elements studied. The subtraction of the (1/v) component has not been indicated, but the summary in Table 5 shows what amount was associated with the (1/v) component in each case. A few comments on the individual detectors follow:

Al^{27} gives clear evidence of a resonance at high energy, the slope corresponding to 9100 ev. There is some indication that some higher energy absorption may also be involved, from a slight departure from linearity at large B. It is interesting that Langsdorf, in experiments on the activation of Al, found evidence of weak resonance absorption at high energy (CP-2638). When a strongly boron-filtered beam was used, the self-absorption cross section of Al was definitely higher than the scattering cross section by an amount of the order of a barn. This might very well have to do with absorption in a broad resonance at 9100 ev.

The data for Cl^{37} are statistically poor because of low counting rates, but a resonance at 1800 ev seems indicated, with a small higher-energy component present as well.

V^{51} gives an excellent straight line corresponding to an energy of 3370 ev.

When the method is applied to Mn^{55}, it shows a very prominent resonance at 261 ev whose absorption can be followed over more than two decades. A small high-energy component has its energy so much higher

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than 261 ev that it is permissible to subtract a constant from the points in order to correct for it. When this is done as indicated, the points marked by crosses are obtained, and a very good linear fit is observed. Rainwater and Havens[4] have found a Mn absorption resonance at 300 ev with velocity-selected neutrons. The discrepancy between 261 and 300 ev is not serious and may be due to one of the following factors:

(a) Uncertainty in the boron content of our discs. As is clear from the previous discussion, an error on this account is not unlikely.

(b) Presence of a small high-energy component. Because the cyclotron resolution triangle includes much more area, on an energy scale, on the high-energy side than on the low, an additional resonance at higher energy would distort the curve somewhat and shift its apparent maximum toward higher energies. Thus, the cyclotron value, if corrected for this effect, would probably be lowered into better agreement with ours.

Cu^{63} shows a prominent resonance at 570 ev. In this case, a fairly sizeable component at higher energy is present. We have tried to correct for it by subtracting a constant, and by so doing we obtained a fairly linear fit. While there is not much to be said for subtracting so large a constant, it is nevertheless true that the value of 670 ev can be determined from the slope at small B and is negligibly affected by this subtraction. Thus, at least one level is definitely fixed by this measurement.

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4 L. J. Rainwater, W. W. Havens, Jr., C. S. Wu, and J. R. Dunning, Phys. Rev. 71, 65, 1947.

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The situation in the case of Cb^{93} appears to be rather complex, and our analysis cannot be said to be completely satisfactory. The amount of (1/v) component subtracted in order to have a smooth curve at low B was in this case quite small -- only 15% as compared to 40% to 90% in the other materials. This is in accord with the fact that Cb has an anomalously small Cd ratio. In other words, we have every reason to believe that there is a prominent resonance at not-very-high energy. Actually, the absorption curve fails to indicate such a situation. A high-energy component at 3590 ev may be separated out without much difficulty. The remaining low-energy points might, by a charitable interpretation, be indentified as a resonance with an energy of 136 ev.

On the other hand, Cb is a rather heavy element and is approaching the part of the periodic table where resonances are generally considered to be rather densely distributed. Therefore, any attempt to separate the activation into a small number of resonances may be fruitless.

CADMIUM-RATIO ANALYSIS

If the integrated flux in the thermal part of the beam is ϕ_{th}, and if the flux per unit energy in the fast beam is ϕ_0/E, then the response of the detector to the open beam (No Cd - No B) may be written:

$$R_{open} = \phi_{th}\,\sigma_{th} + \phi_0 \int \sigma \frac{dE}{E}$$

where σ_{th} is the effective thermal cross section, σ the cross section at energy E. The lower limit of the integral is E_{Cd}, the Cd cutoff energy, about 0.35 ev. With Cd inserted in the beam, we have

$$R_{closed} = \phi_0 \int \frac{dE}{E}$$

The Cd ratio is

$$(6) \qquad CR = \frac{R_{open}}{R_{closed}} = 1 + \frac{\phi_{th}\,\sigma_{th}}{\phi_0 \int \sigma \frac{dE}{E}} \qquad (6)$$

Now if the epi-cadmium activity were of the pure 1/v type, then it follows by simple integration that

$$(7) \qquad \int_{(1/v)} \sigma \frac{dE}{E} = (2/\sqrt{E_0})\,(\sigma\sqrt{E}) \qquad (7)$$

$(\sigma\sqrt{E})$ is a constant independent of the energy, that may be found by taking the value for σ at 2200 m/sec from the Project Handbook and using $E = 0.025$ ev. This would give

$$(8) \qquad \int_{(1/v)} \frac{\sigma\, dE}{E} = 0.535\, \sigma_{22} \qquad (8)$$

where σ_{22} is the activation cross section at 2200 m/sec.

The total epi-cadmium activation is

$$(8') \qquad \int_{(1/v)} \sigma \frac{dE}{E} + \int_{(res)} \sigma \frac{dE}{E} = \int_{(1/v)} \sigma \frac{dE}{E} \left(1 + \alpha\right) \qquad (8')$$

where α is the ratio of resonance activation to (1/v) activation. α was determined from the analysis of the boron-absorption curves and is listed in Table 5.

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equation 6

We now have enough information to solve (6) for the flux ratio (ϕ_{th}/ϕ_{0}). But before we do this, we note that σ_{th} is not the cross section at 2200 m/sec, but is smaller than this, for two reasons:

(1). The pile temperature, or neutron-beam temperature, is rather high, about 400° K. This involves a reduction factor of 0.86.

(2). The effective cross section for a Maxwellian distribution and 1/v detector is smaller than that corresponding to the beam temperature by a factor 0.89.

Altogether we get $\sigma_{th} = 0.765\ \sigma_{22}$. As a result,

$$\frac{\phi_{th}}{\phi_{0}} = (CR-1)\left(\frac{1+\alpha}{1.43}\right) \qquad (9)$$

Equation 9

(9) may be considered a calibration of the fluxes. Since it may be applied to the various elements we studied, we get a number of independent calibrations, the consistency of which throws light on the validity of the separation of the epi-cadmium activity into "1/v" and "resonance" components.

Taking the Cd ratios from Table 3 and the values α from Table 5, we get the column (ϕ_{th}/ϕ_{0}) of Table 5. This ratio exhibits reasonable constancy over a wide range of Cd ratios and values of α (although it is determined with low precision when α is large).

The average of 27.8 may then be adopted as a characteristic number for the beam from the top of the pile, at least under the conditions of this experiment. The fairly small fluctuations about this average induce confidence that the separation of the epi-cadmium activities was not essentially in error.

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The column $\int \sigma \frac{dE}{E}$ of Table 5 gives the resonance activation integral for all the activity above the Cd cut-off. The last column, $\int \sigma_{res} \frac{dE}{E}$, gives the same, but with the (1/v) component subtracted. Both the last two columns are proportional to the thermal cross sections tabulated in the Project Handbook and reflect any errors in these values. None of the other entries on Table 5, however, depend on the tabulated cross sections.

ANALYSIS OF INDIUM ACTIVATION

To throw additional light on the questions of the calibration of the fluxes and the resonance activation of indium, we measured the cadmium ratio for the 54-min activity rather carefully in our geometry. For work on resonance absorption in the Argonne Laboratory, indium has in the past been used as a standard. The value for $\int \sigma dE/E$ for the absorption by indium has been estimated as 3000 b ± 15% by integrating cross-section curves obtained by modulated-beam methods.[9] However in these experiments, the resolution was not good enough to resolve the 1.4 ev level, and one had to resort to somewhat uncertain procedures to try to obtain the true cross-section curve from the experimental data. This accounts for the large percentage error attached to the value of 3000b. It would be desirable to have an independently obtained standard for use in resonance-absorption experiments, and such a standard is supplied by the present experiment and the determination of $[\phi_{Al}/\phi_{1/2}]$. It is the purpose of the present section to see how close is the agreement with the estimate of 3000b as the resonance-absorption integral for indium.

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9. W.W. Havens, C.S. Wu, L.J. Rainwater, and C.L. Meaker, Phys. Rev. 71: 165 (1947).

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An In foil of thickness 0.51x10^{-2} gm/cm^2 was activated with increasing thicknesses of Cd. The result is shown in Figure 10. A plateau reached after 0.15 gm/cm^2 Cd indicates that at this point all the thermal activation had been removed while the resonance activation was unaffected.

Fig. 10

The value of σ_{th} for the 54-min activity is (150) (.89) (.86) = 114.6b. Using equation 6 (6) and the value of 2.58 for the Cd ratio, we solve for $\int \sigma \frac{dE}{E}$ and get 2015b. This is subject to a correction because the foil is not infinitely thin. If the resonance has a Breit-Wigner shape with maximum cross section σ_0, then the ratio of activation per atom to that for an infinitely thin foil is (collimated-beam geometry)

$$\frac{Act}{(Act)_0} = 1 - \frac{t}{4} + \frac{t^2}{8} + \cdots \qquad (10)$$

where $t = N\sigma_0$ and N is the number of atoms per cm^2. For the In foil used, this factor is 0.983 if we take for σ_0 the value 26,000b indicated by the cyclotron experiments. Note, however, that this correction is very small, so that errors in the previous experimental value of σ_0 do not influence the result appreciably.

The resonance integral for In 54-min corrected to "infinitely thin" is now 2050b.

Now, using the fact that the branching ratio in the 1.4-ev level for the 54-min and 13-sec periods is the same as at thermal, it follows that the total resonance integral (including both 54-min and 13-sec) is

$$\int \sigma \frac{dE}{E} = 2047 \left(\frac{150 + 54}{150} \right) = 2790 \text{ b}$$

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Thus, it might be concluded that the value of 3000b was high by 7.5%. This, however, is barely outside our error of 5% in the determination of (ϕ_{Cd} / ϕ_0), and well within the original uncertainty of 15% that applied to the value of 3000b. Furthermore, the value of 3000b presumably contains a finite, although small, contribution from the In^{113} isotope—perhaps of the order of one or two percent; this is not included in the value of 2790b. The good agreement here inspires further confidence that the separation of activities into components, which led to the determination of (ϕ_{Cd} / ϕ_0) was a valid procedure.

SHAPES OF THE RESONANCE LEVELS

The previous analysis determined the position and strength of a resonance level for each target. (By strength, we mean $\int \sigma \frac{dE}{E}$ taken over the level). However, nothing could be inferred about the shape of the level. To do this directly, it would be necessary to carry out self-absorption experiments for each detector, and this was not done in this series of measurements. Strictly, then, we can say nothing about the structure or width of the absorption region, except that it is sufficiently narrow to give straight-line absorption.

By way of speculation, however, it is interesting to see what shape the resonances would have to possess if they were simple Breit-Wigner levels, and if in each case the lowest level was singly responsible for the thermal cross section.

We write the Breit-Wigner formula as

$$\sigma(cm^2) = 2.6 \times 10^{-18} S \frac{a \Gamma_n}{\Gamma \sqrt{E}} \frac{1}{1 + 4(E - E_1)^2 / \Gamma^2} \qquad (11)$$

Here S is a spin factor of order one. Γ is the full width at half maximum and is given by

$$\Gamma = \Gamma_\gamma + a\sqrt{E}$$

where (Γ_γ) is the gamma-ray partial width and $(a\sqrt{E})$ is the neutron partial width. We make no allowance for Doppler broadening. (E_1) is the resonance energy. Integrating (11) over the line, and assuming the line width is sufficiently small so that $(E - E_1)$ is the only variable, we get

$$\int_{res} \frac{\sigma\, dE}{E} = \frac{2.6 \times 10^{-18} S}{E_1^{3/2}} \frac{\pi}{2} \left(\frac{a\Gamma_\gamma}{\Gamma_\gamma + a\sqrt{E_1}} \right) \qquad (12)$$

Now far away from the line, near the thermal region, we may neglect E/E_1. Therefore,

$$\sigma \longrightarrow 0.65 \times 10^{-18} S \frac{a\Gamma_\gamma}{E_1^2} \frac{1}{\sqrt{E}}$$

Therefore, the $(1/v)$ component of the epi-Cd activation would be

$$\int_{(1/v)} \frac{\sigma\, dE}{E} = 1.30 \times 10^{-18} S \frac{a\Gamma_\gamma}{E_1^2} \frac{1}{\sqrt{E_c}}$$

and according to the definition (8')

$$\alpha = \pi \frac{\sqrt{E_1 E_c}}{(\Gamma_\gamma - a\sqrt{E_1})}$$

Here everything is known except Γ, so one may solve for the latter. The calculated values of Γ are listed in column 3 of Table 6. It will at once be noted that these values are extremely large compared to the values of about 0.1 ev to which one is accustomed in the case of heavy

TABLE 6.

Level Constants on One-Level Hypothesis

Target	Isotopic $\int \frac{\sigma_a dE}{E}$ res $\times 10^{-24}$ cm²	Γ (ev)	Γ_n (ev)	S (ev)	σ_0 $\times 10^{-24}$ cm²	σ_0 S $\times 10^{-24}$ cm²	σ_a(kT) $\times 10^{-24}$ cm²
Na^{23}	.0510	322	7.8	.0365	.17	1.5×10^3	14.
Al^{27}	.0195	1120	11.7	.395	.10	2.8×10^2	1.1
Cl^{37}	.0258	1000	23.6	.0205	.030	1.5×10^3	27.
V^{51}	.358	915	15.8	1.00	.84	7.7×10^2	13.
Mn^{55}	8.16	22.6	1.40	.137	60.5	1.0×10^4	18.
Cu^{65}	1.00	48.0	2.01	.0796	7.5	4.6×10^3	2.4
Cb^{93}	(.0163)						
	(.0133)						

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elements. This is to be interpreted (provided the one-level hypothesis is correct at all) by assuming the neutron width, $a\sqrt{E}$, to be very large for these resonances; it is much easier to understand strong variations with atomic number of this width than of the gamma-ray width. Thus the quantity (a) may be obtained to good approximation as the ratio of Γ to $\sqrt{E_r}$. This is listed in the next column.

Simultaneously, the gamma-ray width may be obtained from (12). The result, tabulated in Table 6 (to within the spin factor S), verifies the hypothesis that the neutron width accounts for practically the total width. Except in the case of V, the gamma widths are not greatly different from those that occur in known resonances of heavy elements.

Although in this experiment only the activation of the material in question was studied, the predominance of the neutron width indicates that the resonance should actually be much more prominent in scattering than in absorption, the ratio of the two cross sections being $a\sqrt{E}/\Gamma_\gamma$. Columns 6 and 7 list the activation and scattering cross sections at exact resonance. The remarkably large values of scattering cross section suggest that self-absorption experiments be carried out with appropriately filtered beams*.

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* Goldhaber has reported an anomalously large resonance scattering in the case of manganese. (Bull. Amer. Phys. Soc. 21, 6 (1946).

* Langsdorf, Seidl, and Harris report that σ_{sc} for Manganese is at least of the order of four thousand barns. Phys. Rev. 12, 168 (1947).

It is to be noted that if the resonance scattering cross sections are really this large, the data of this experiment are subject to correction for the thicknesses of foil used (these were originally chosen to insure thinness for absorption). This question must be postponed until final information is available on resonance scattering cross sections.

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The last column gives the scattering cross section at (kT) that would be contributed by this level if no other scattering (such as potential scattering) were present. Now in fact with potential scattering present, the scattering amplitudes due to the two effects will either add or subtract. Thus the final cross section would be expected to differ markedly from that given in the last column. Let us consider the cases of Mn and Cu, for which it seems most nearly probable that the one-level hypothesis is correct. We take into account that in this part of the periodic table, the scattering cross section due to potential scattering alone is about 4-6 barns. Nevertheless, the measured value for Mn is 2.5b and for Cu (normal isotopic mixture), 7b. It thus appears that resonance and potential scattering amplitudes should add in the case of Cu^{65}, but subtract in the case of Mn^{55}.

In conclusion of this section, we may say that the one-level hypothesis applied to Mn gives a reasonable account of the observed effects. The case of Cu is less clear, but the one-level picture is not implausible. As for the other substances, the validity of the one-level hypothesis is highly problematical.

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REFERENCES

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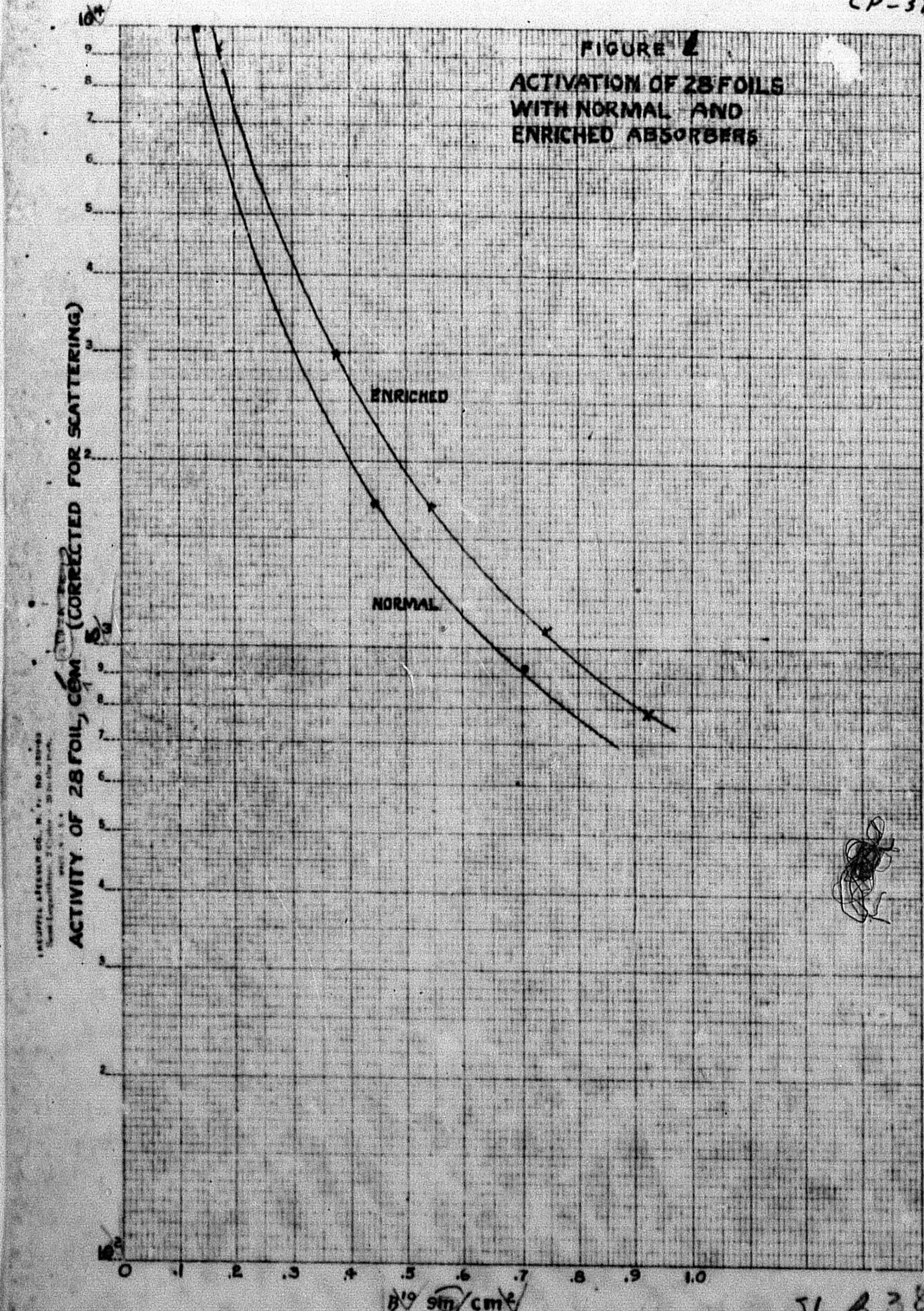
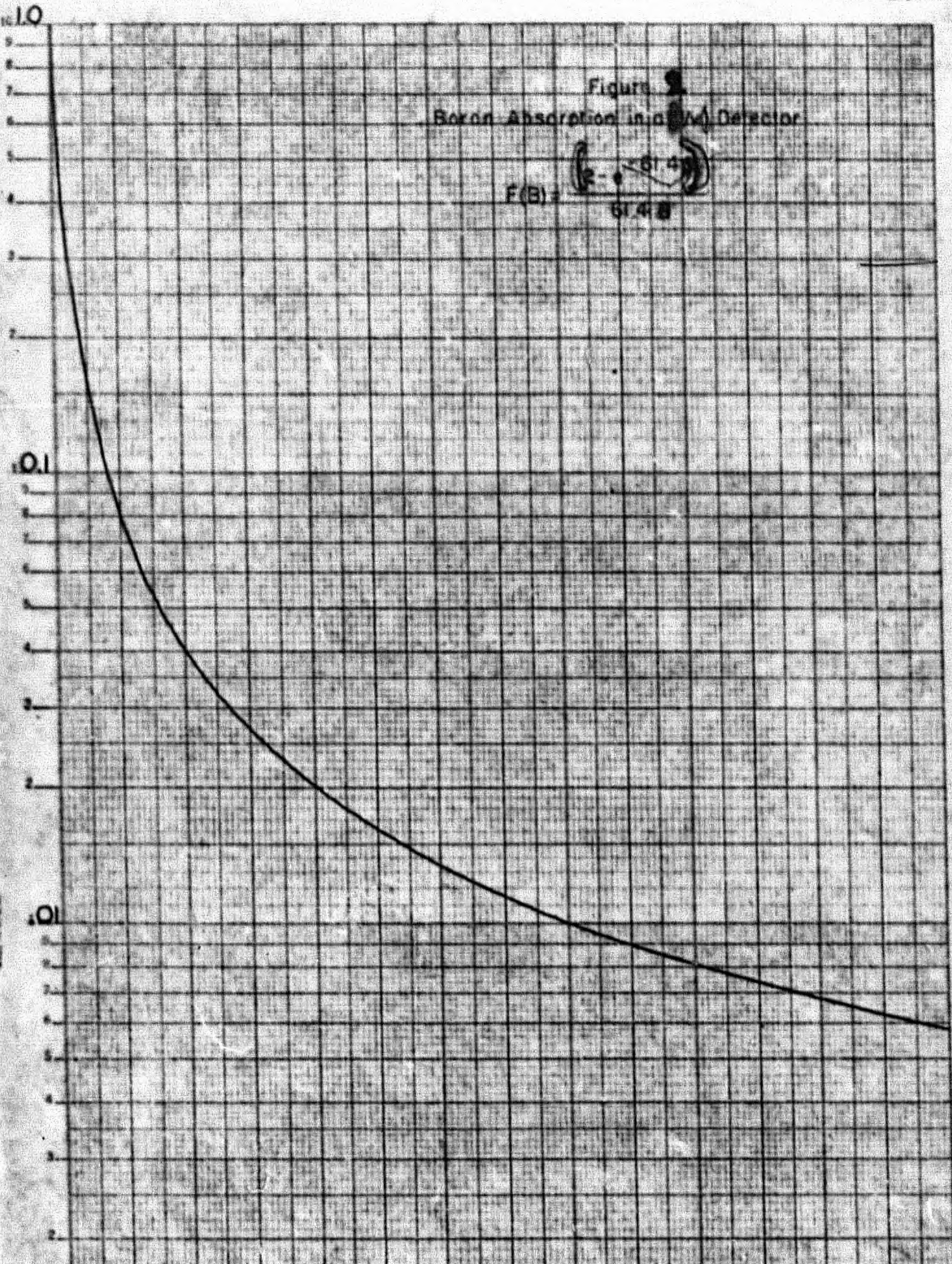


26 B 38


1.0
0.1
.01
.001
0
.2
.4
.6
.8
1.0
1.5
2.0
2.5
Figure [redacted]
Boron Absorption in a [redacted] Detector
F(B) =
61.4 B

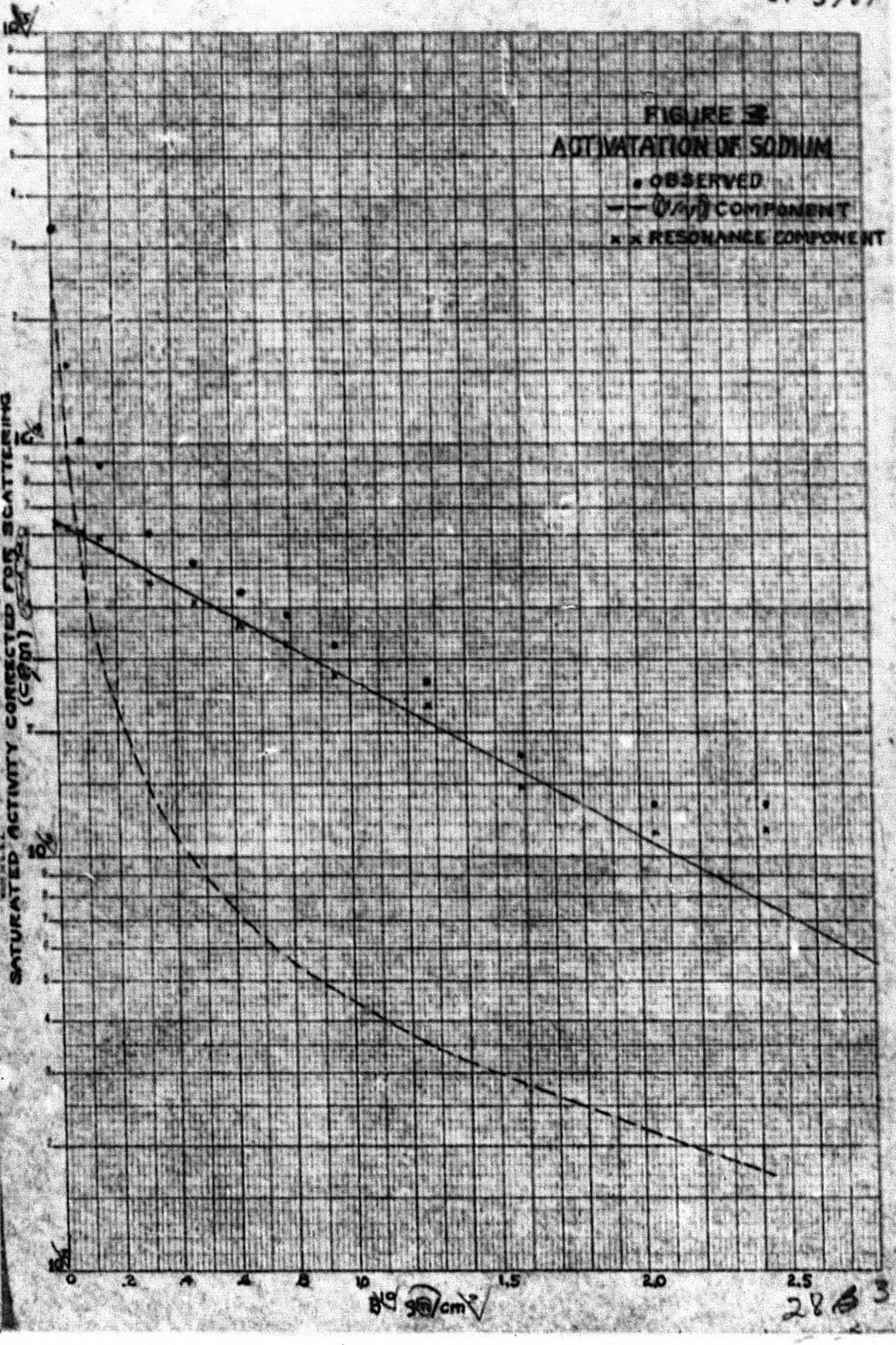


FIGURE 3
ACTIVATATION OF SODIUM
• OBSERVED
— — (1/v) COMPONENT
x x RESONANCE COMPONENT
SATURATED ACTIVITY CORRECTED FOR SCATTERING
(CPM)
0
.2
.4
.6
.8
1.0
1.5
2.0
2.5
B¹⁰ gm/cm²

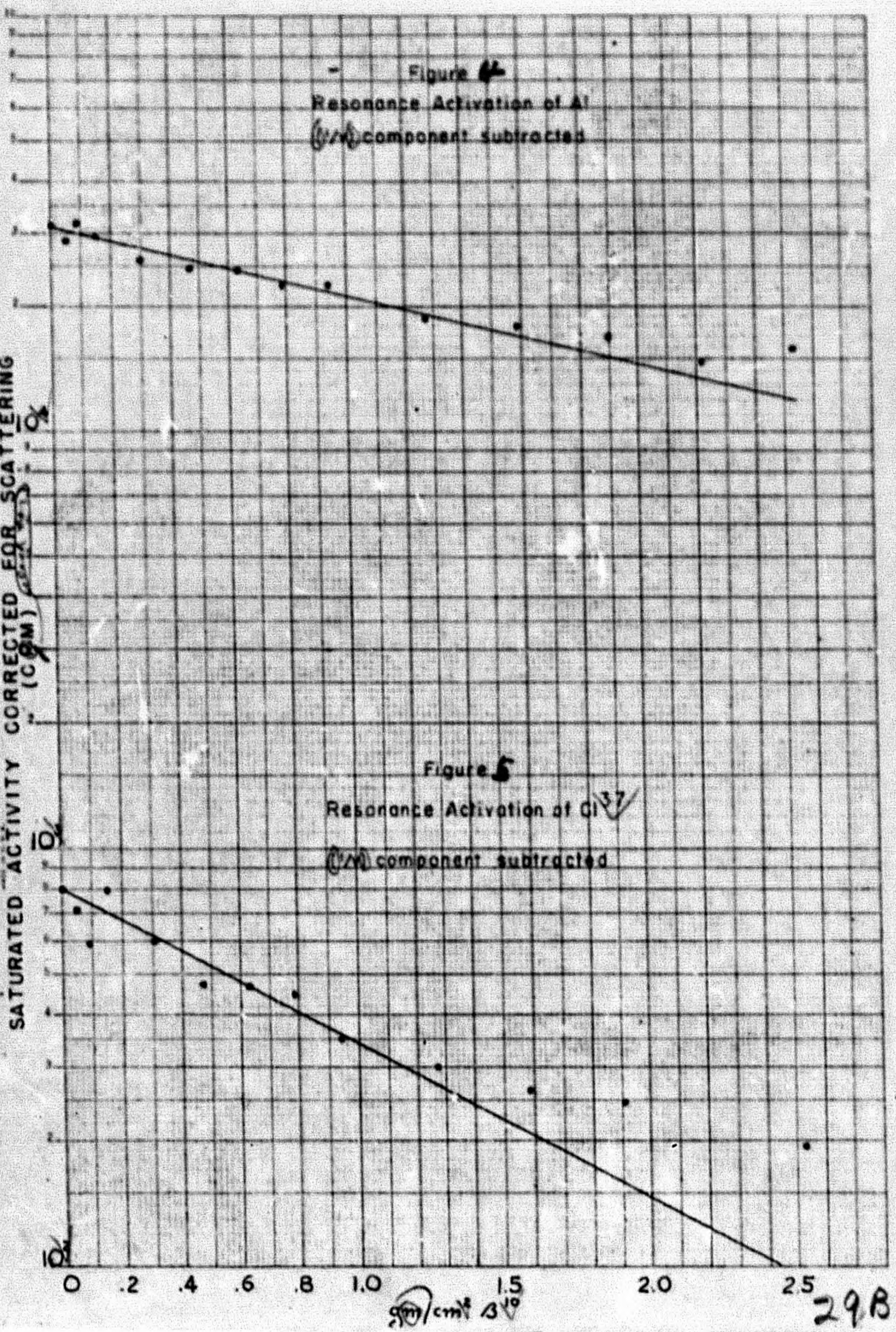


Figure 4
Resonance Activation of Al
(1/v) component subtracted
Figure 5
Resonance Activation of Cl37
(1/v) component subtracted
SATURATED ACTIVITY CORRECTED FOR SCATTERING
(C/M)
0
.2
.4
.6
.8
1.0
1.5
2.0
2.5
gm/cm² B10

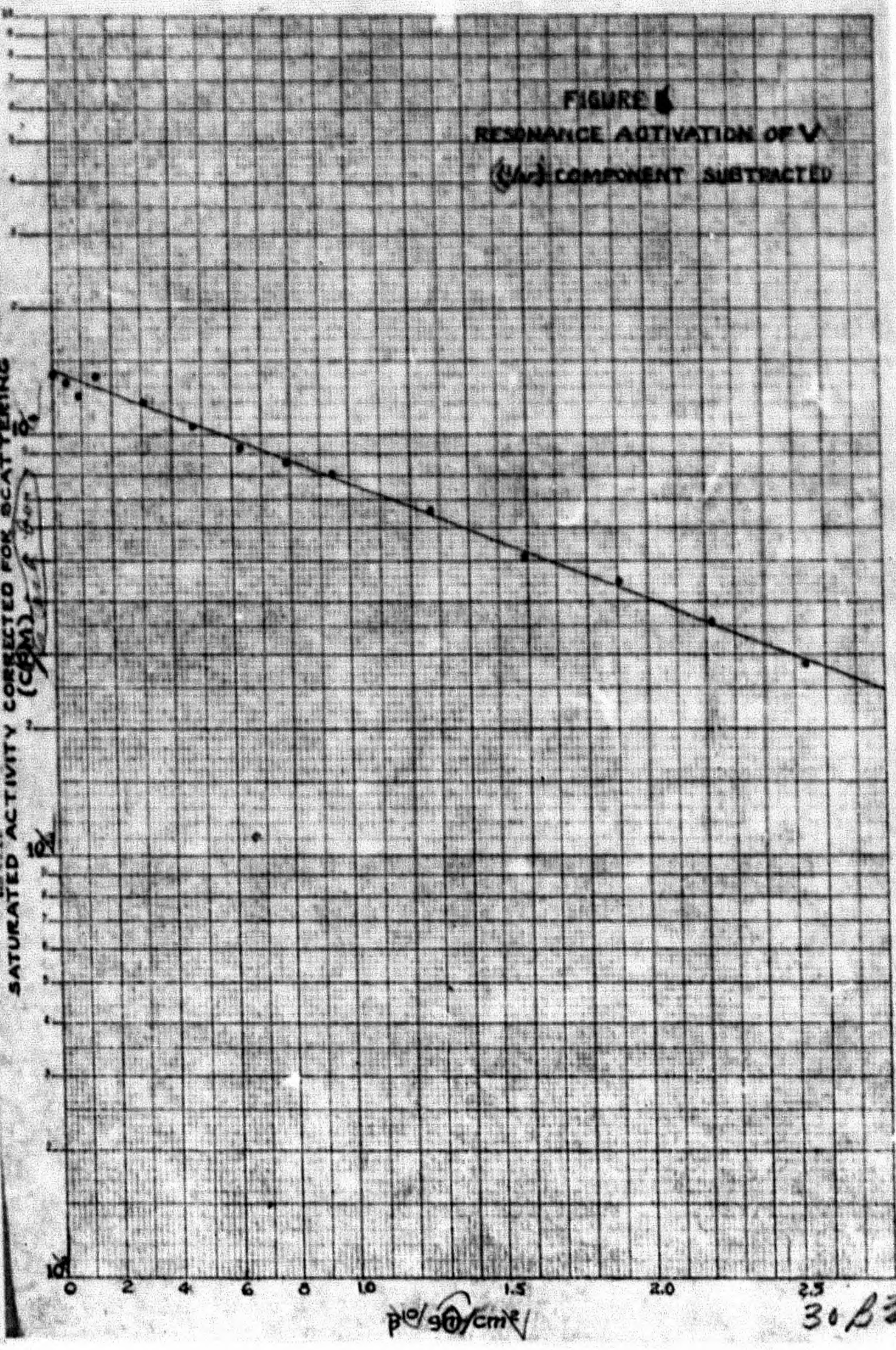


FIGURE
RESONANCE ACTIVATION OF V
COMPONENT SUBTRACTED
SATURATED ACTIVITY CORRECTED FOR SCATTERING (CPM)
0
2
4
6
8
1.0
1.5
2.0
2.5

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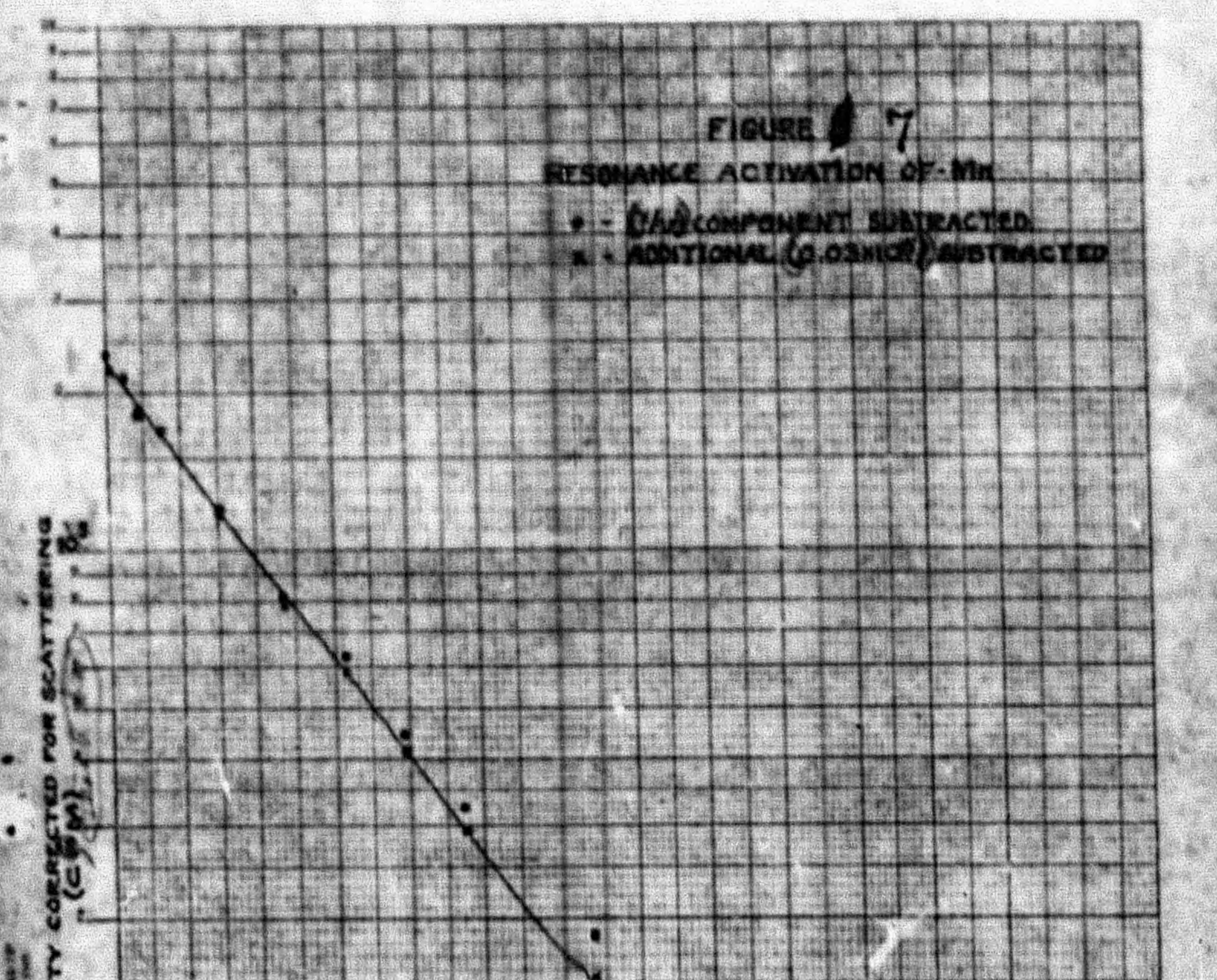

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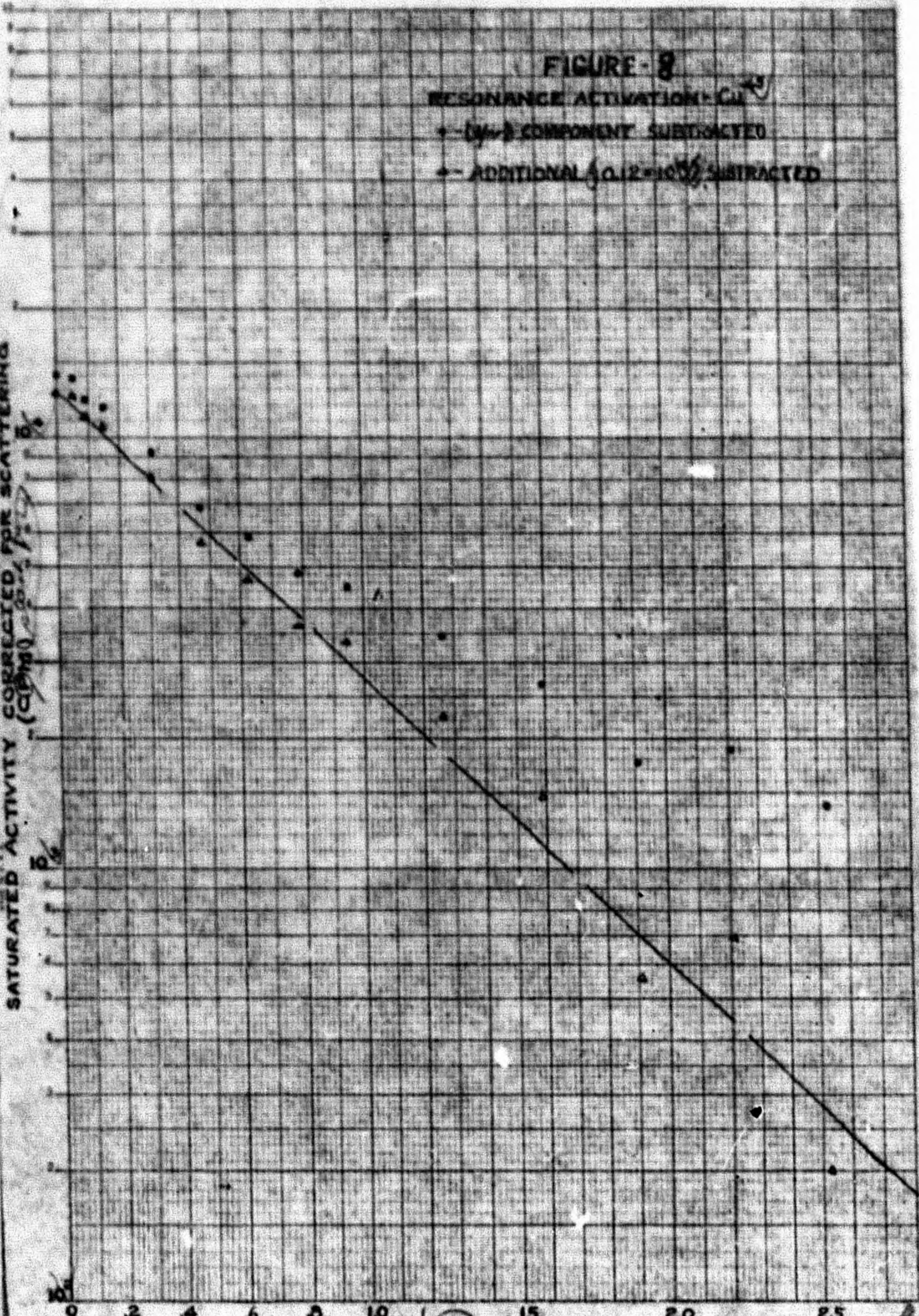
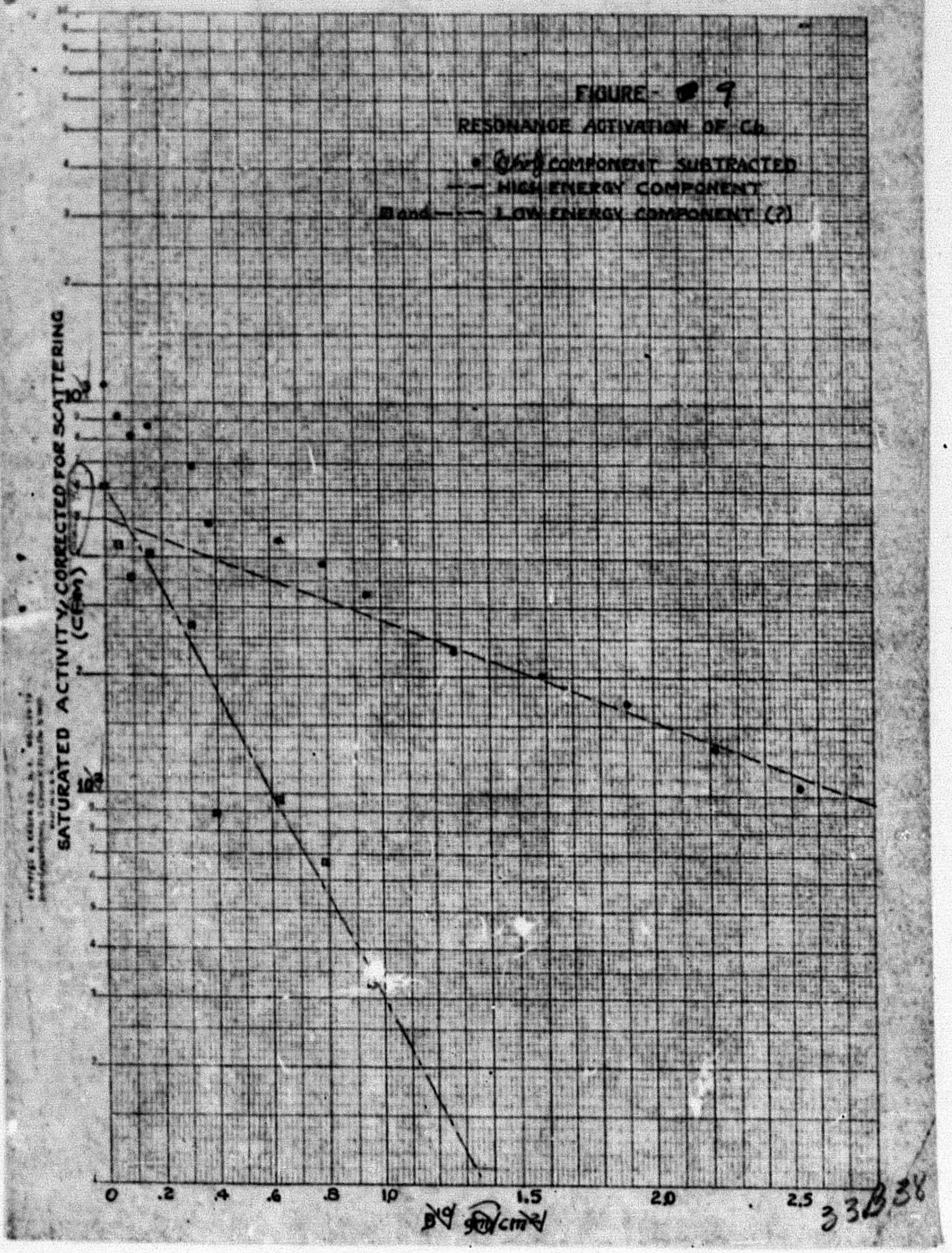


FIGURE - 8
RESONANCE ACTIVATION - Cu
+ - (γ,n) COMPONENT SUBTRACTED
▲ - ADDITIONAL (0.12 = 10%) SUBTRACTED
SATURATED ACTIVITY CORRECTED FOR SCATTERING (CPM)
10
0
.2
.4
.6
.8
1.0
1.5
2.0
2.5
β gm/cm²

CP-3781



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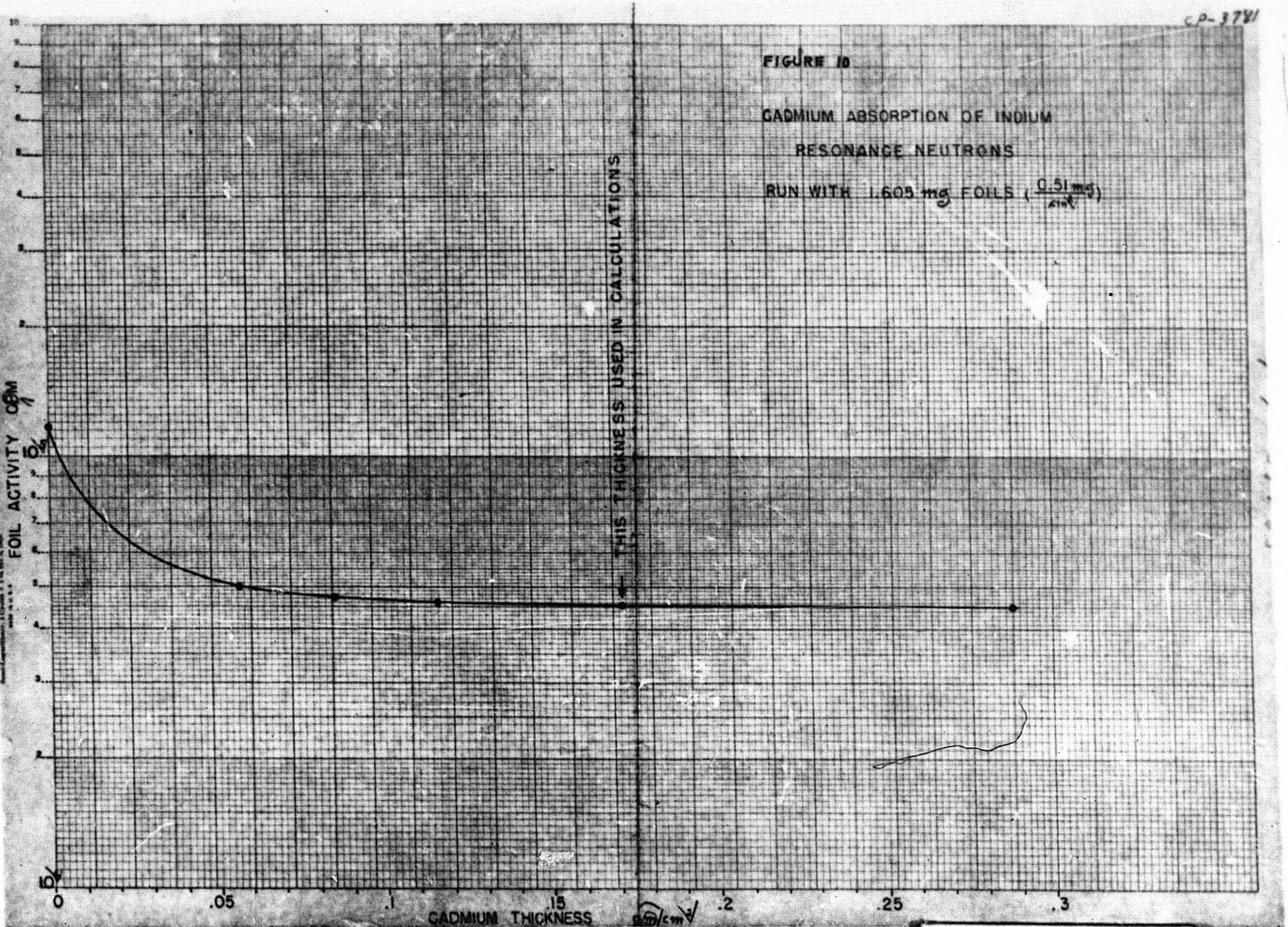

FIGURE 10
CADMIUM ABSORPTION OF INDIUM
RESONANCE NEUTRONS
RUN WITH 1.605 mg FOILS (0.51 mg/cm²)
THIS THICKNESS USED IN CALCULATIONS
FOIL ACTIVITY CPM
CADMIUM THICKNESS gm/cm²
0
.05
.1
.15
.2
.25
.3