

expect the value of D_J to increase in going from BrCN to ICN due to the larger stretching of the C—X bond. The rather large limits of error prevent any definite conclusions here, although the value of D_J for ICN is larger than the average BrCN value.

It is interesting to compare the distortion constant values obtained here for the methyl halides with those calculated by Slawsky and Dennison.⁷ Using dimensions and force constants determined principally from infra-red data, they obtained values of D_J which are roughly one-tenth of the values given here. Their computed values of D_{JK} have the correct order of magni-

⁷Z. I. Slawsky and D. M. Dennison, *J. Chem. Phys.* **7**, 509 (1939).

tude, being 1.6 to 2.5 times the experimental values, but have the opposite algebraic sign. Frequencies of the unsplit lines for $K=0$ computed with their values of D_J but with the I_B evaluations reported here differ by about two or three megacycles from the observed frequencies. Within the limits of experimental error, however, the variation of the line frequency shift due to centrifugal distortion expressed as a function of the values of J and K appears to be correctly predicted by Eq. (1).

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Pile Neutron Absorption Cross Sections

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Neutron absorption cross sections for over 50 elements have been measured in the neutron flux of the Argonne heavy water reactor. Measurements were made by observing the oscillating component of reactor power as a neutron absorber sample was oscillated in and out of the central flux of the pile. Calibration was effected with boron.

I. INTRODUCTION

IT was originally suggested by Fermi that neutron absorption cross sections for pile neutrons could be measured by inserting absorbers in the center of a pile in equilibrium and adjusting one of the control rods to compensate for the absorption. The compensating motion, Δl , would then be proportional to the absorption, $n_a \sigma_a$, and could be evaluated in terms of a standard such as boron. This method, termed the "danger coefficient method" (because the absorber was thought of as a poison to the reactor), was applied successfully at Argonne by Wattenberg in the measurement of about 20 elements.

A modification of the "danger" or static method was later suggested by Fermi and Wigner. This method was dynamic in character and consisted in oscillating an absorbing sample in and out of the reacting flux of a pile, while observing the oscillating component of pile power, $\Delta \dot{p}$, and the mean pile power \bar{p} ($\Delta \dot{p} \ll \bar{p}$). For a thin sample:

$$\Delta \dot{p} \propto \bar{p} n_a \sigma_a,$$

where n_a and σ_a are the number of absorbing nuclei and the neutron absorption cross section, respectively.

The apparatus for performing these measurements was developed by a group under the direction of A. Langsdorf at the Argonne National Laboratory.

Measurements were made later on 55 elements by the authors.

II. APPARATUS

The equipment will be described in a paper by Langsdorf and his collaborators in a future publication. Briefly it consists of:

(1) A vertical mechanical oscillator which periodically lowers a 75-cc "can" containing the absorbing material into the center of the reacting neutron flux for 10 sec. and then raises the sample out of the flux for 10 sec. The stroke is five feet in length. All parts that oscillate in the reactor flux are made of Dow-Metal FS-1 with the exception of the sample cans, bronze clamp, and graphite bearings.¹

(2) A BF_3 ionization chamber to record both the total current, $i \propto \bar{p}$, and the oscillating current, $\Delta i \propto \Delta \dot{p}$. This neutron chamber is placed in the thermal column of the reactor, which location is suitable for indicating the power level of the pile.

(3) A bridge circuit (20 sec. sensitivity) with ohmic

¹ Measurement of the neutron absorption cross section of Mg by an all-Al oscillator was shown by Langsdorf and his group to be about 0.07×10^{-24} cm². This approximate value was also confirmed by Wattenberg (Argonne, 1945) and by Goldhaber and Muehlhaue (University of Illinois, 1942). Dow metal FS-1 which consists of ~ 95 percent Mg, five percent Al, and 0.15 percent Mn has therefore an effective neutron absorption cross section of about 0.1 barn and is three times less absorptive per unit volume than is Al.

balancing resistor, R , which measures directly² the ratio $\Delta i/i$.

III. ADJUSTMENTS AND FLUX CONDITIONS

The adjustment of the in-position of the sample was determined by finding the in-point from which graphite (an almost pure scatterer) could be oscillated yet produce no pile effect. This position, so determined,

TABLE I. Neutron absorption cross sections.

Element	σ_{pile} (barns)	Comments	Chemical forms
B	710	standard	B, B ₂ O ₃ , H ₃ BO ₃
Na	0.52		Na, NaF
Mg	0.06		Mg
Al	0.22		Al
Si	0.16		SiO ₂
S	0.51		S, CS ₂
Cl	31.5		C ₂ Cl ₆
K	2.11		K, KF
Ca	0.43		CaF ₂ , CaCO ₃
Sc	31.8	impure	Sc ₂ O ₃
Ti	5.88		Ti
V	4.93		V ₂ O _{3,72}
Cr	3.05		Cr, Cr ₂ O ₃
Mn	12.3		Mn
Fe	2.48		Fe, Fe ₂ O ₃
Co	35.7		Co, CoO
Ni	4.37		Ni, NiO
Cu	3.71		Cu, CuO
Zn	1.09		Zn
Ga	3.10		Ga
Ge	2.64		GeO ₂
As	5.46		As ₂ O ₃
Se	12.2		Se
Br	8.83	thick	CBr ₄
Sr	1.53		SrF ₂
Zr	~0.4		ZrO ₂
Cb	1.51		Cb, Cb ₂ O ₆
Mo	3.04		Mo, MoO ₃
Ru	6.30	~150 mg/cm ²	Ru
Rh	172	~15 mg/cm ²	Rh
Pd	10.3	thick	Pd
Ag	90	~5 mg/cm ²	Ag
Sn	0.72		Sn
Sb	8.15	~400 mg/cm ²	Sb, Sb ₂ O ₃
Te	5.82		Te
I	9.23	~250 mg/cm ²	I, CHI ₃ , PbI ₂
Cs	35.8		CsF, Cs ₂ SO ₄
Ba	1.35		BaF ₂
La	9.01		La ₂ O ₃
Ce	~0.65	small sample	Ce ₂ O ₃
Nd	52	perhaps rare earth impurity	Nd ₂ O ₃
Sm	~8200		Sm ₂ O ₃
Gd	36,500		Gd ₂ (SO ₄) ₃
Hf	171	~20 mg/cm ²	HfO ₂
Ta	36	~130 mg/cm ²	Ta, Ta ₂ O ₅
W	24	~130 mg/cm ²	W, WO ₃
Re	120	~15 mg/cm ²	Re
Ir	~470	~10 mg/cm ²	Ir
Pt	13.5		Pt
Au	~157	~3.5 mg/cm ²	Au
Hg	~380		HgO, Hg(CN) ₂
Tl	3.65		Tl
Pb	0.16		Pb
Bi	0.038		Bi

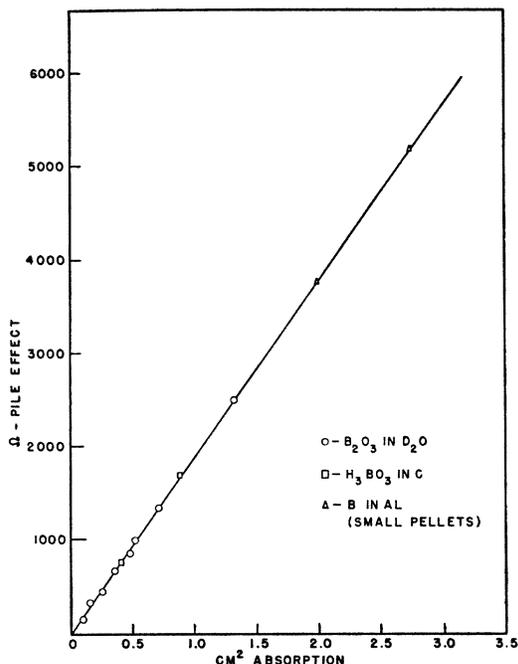


FIG. 1. Pile neutron absorption in boron vs. the pile effect (Ω).

also nearly coincided with the maximum flux position as determined by the activation of a series of Au foils placed at equal intervals in the central vertical tube of the reactor. This latter point should be, and in fact was, slightly higher in the tube than the point of maximum reacting flux.

An analysis of the pile flux was made by measuring the cadmium ratio for thin Au (0.15 mg/cm²) and assuming the Au resonance capture integral³ (in excess of $1/v$ absorption) to be 1300 b. A value⁴ of 93 b was taken for the Au thermal absorption cross section. Since boron was used to calibrate the pile effect, the measured pile cross section, σ_{pile} , can be written as

$$\sigma_{pile} = \sigma_{th} + k \Sigma_a$$

where Σ_a is the resonance absorption integral for other than $1/v$ absorption. The $1/v$ resonance absorption was shown to be $\sim 0.45 \sigma_{th}$ by several methods. Therefore:

$$k = \frac{\sigma_{th-Au}}{(Cd \text{ ratio} - 1)_{Au} (0.45 \sigma_{th-Au} + \Sigma_{a-Au})}$$

For a Cd-ratio of Au equal to 2.25, k was evaluated as 0.054. The pile absorption cross section is therefore:

$$\sigma_{pile} = \sigma_{th} + 0.054 \Sigma_a$$

It should be understood that in the above Σ_a is the "effective" resonance absorption integral not including

² R is measured in ohms (Ω) and is adjusted to buck the oscillating component of current, Δi . This is done in such a way that $R \propto |\Delta i|/i$. The pile absorption effect is thereby translated into an " Ω -effect." Since the absorption is proportional to $n_a \sigma_a$ (Section I), then $\Omega \propto n_a \sigma_a$.

³ M. Goldhaber, University of Illinois (Breit-Wigner fit to Columbia data).

⁴ A. Wattenberg, Argonne National Laboratory (mechanical velocity selector).

1/v absorption. In a number of cases the samples used were so thick that the effective resonance absorption integral of the self-protected sample was considerably less than the true resonance absorption integral.

IV. CALIBRATION

Boron standards were run in various densities as H_3BO_3 fine mixture in graphite, B_2O_3 in D_2O , and as B in Al. All methods yielded the same calibration curve linear to about 6000Ω . In Fig. 1 is plotted the Ω -effect vs. cm^2 absorption of boron. The thermal cross section of boron was taken to be 710 b. The slope of the curve is $1890\Omega/cm^2$ which value was used throughout in the calculation of σ_{pile} .

V. MEASUREMENTS

Measurements were made by first oscillating the empty sample can plus empty powder can or bottle. That is, the blank or background effect for each sample was first determined. This was run several times. Next the absorbing sample with its container was oscillated, and the difference between the first and second measurements yielded the effect due only to the absorber.

To insure complete linearity all pile effects were kept at less than 3500Ω . The Dow metal empty sample can and moving hangar rods gave a reading of 730Ω . This was the least value to be subtracted from all others. For most samples, the net effect was determined by numbers of the following approximate magnitudes:

$$\text{net } \Omega = 3000 \pm 10 - 1000 \pm 10 = 2000 \pm 15.$$

This error is <one percent, and a given sample during a typical two-day run generally repeated to about two percent. For different samples from one run to any other (i.e. at least one month apart) measurements would repeat to less than five percent.

Each measurement took approximately 20 minutes since this much time was necessary for the pile to reach a new equilibrium. Though the readings were independent of pile power, control rod adjustments were made for each reading to bring the reactor back to about the same power level (~ 0.6 kw). Other factors

that might have second- or third-order effects were also kept constant. Some of these were heavy water level in the reactor tank, and the positions of the shim rods.

VI. PREPARATION OF SAMPLES

The samples were the purest obtainable, being either reagent grade compounds or substances specially purified by S. Rasmussen. All materials were analyzed spectroscopically for traces of contaminants with special emphasis on impurities having a large neutron absorption cross section.

Most samples were of elemental, oxide, fluoride, carbonate, or sulfate form. They were run unmixed, mixed with graphite, or dissolved in D_2O . This latter substance had a negative pile effect owing to its high slowing-down power and low thermal absorption. Each element was run in the form of at least two independent samples, and usually in more than one chemical form. The average number of runs per cross section was four. This does not include blank or calibration runs.

VII. RESULTS

Table I lists the average values obtained for σ_{pile} . The internal consistency, except for strong resonance absorbers like Ta and W, was better than to five percent. Materials of this latter type, however, defy accurate measurement since in order to have the contribution to σ_{pile} from Σ_a linear with sample thickness, the amount of the sample had to be too small to measure properly. For this reason many of the pile absorption cross sections given in Table I are dependent on their exact thicknesses. Furthermore, in these cases, it is not possible to resolve σ_{pile} into σ_{th} and Σ_a unless σ_{th} is known. That is, Σ_a is in general only an effective value dependent on sample thickness in a non-linear way. Those substances having no comment on thickness may be assumed to have a pile cross section given by $\sigma_{pile} = \sigma_{th} + 0.054\Sigma_a$, where Σ_a is the true resonance absorption integral. A list of Σ_a values is given by Harris, Muehlhause, and Thomas.⁵ These can be used to determine σ_{th} from σ_{pile} .

⁵ Harris, Muehlhause, and Thomas, Phys. Rev. **79**, 11 (1950).