in a water solution at room temperature containing 0.1883 mole/liter H_3BO_3 and a Ra-Be source. He obtained a value of 0.0358 ± 0.0030 for the fraction of neutrons captured in the epicadmium region above 0.5 v.

For σ_B = 755b and σ_H = 0.332b, $v\Sigma_B$ = 18840 sec^{-1} and $v\Sigma_H$ = 4855 sec^{-1} for this solution. Then $\tau_{th} = 1/(v\Sigma_B + v\Sigma_H) = 42.2 \times 10^{-6}$ sec. As a result, the slowing-down time from Eq (4) is t_s = 1.54 ± 0.13 μsec. The atom density of boron is only 1/600 that of hydrogen in this solution, so the slowing-down time in pure water will be the same from 5 Mev to 0.5 v. Krieger (*2*) has calculated a value of 1.6 μsec for slowing down to 0.35 v in water at 293 °K. Haynam and Crouch (*3*) have obtained a value of 1.7 μsec for slowing down to 0.35 v and 1.1 μsec to 0.8 v with a Monte Carlo calculation. Effects due to chemical binding were neglected. Crouch's measured value of 5.2 μsec (*4*) to 0.35 v seems to have a systematic error. Walker's experiment would indicate little effect due to chemical binding.

This method of extracting a mean life is valid if the longest slowing down time is small compared to the mean thermal life so that the chance of capture is strictly proportional to the individual slowing down time, independent of its length. As t_s/τ_{th} becomes larger the calculated result obtained is smaller than the true value. For Walker's experiment, the bias may be of the order of 2% which is small compared with the experimental error.

Another quantity of interest may be obtained from measurements with a $1/v$ detector in any medium. Assume a small amount of $1/v$ poison is added to the medium but not enough to perturb the neutron distribution. The probability of capture of a neutron in the poison is proportional to the time the neutron spends in the medium,

$$-dN/N = v\Sigma_p\, dt = k dt.$$

If N neutrons are emitted by the source,

$$A_{Cd}/A_0 = \frac{\int_{i=1}^{N} N_i\, t_{ie}/N,}{\int_{i=1}^{N} N_i\, t_{i0}/N,} \qquad (5)$$

$$A_{Cd}/A_0 = \bar{l}_e/\bar{l}_0$$

where $\bar{l}_e$ is the mean epicadmium life of a neutron and $\bar{l}_0$ is the mean (total) life. For a $1/v$ medium $\bar{l}_0 = \tau_{th}$. Since epicadmium capture is included in the definition of $\bar{l}_e$, $t_s \geqq \bar{l}_e$.

REFERENCES

1. R. L. Walker, U. S. Atomic Energy Commission Document, MDDC-414 (October 22, 1946).
2. T. J. Krieger and F. D. Federighi, Neutron slowing down times and chemical binding. *Trans. Am. Nuclear Soc.* **2**, 102–103 (November, 1959).
3. G. E. Haynam and M. F. Crouch, *Nuclear Sci. and Eng.* **2**, 626–630 (1957).
4. M. F. Crouch, *Nuclear Sci. and Eng.* **2**, 631–639 (1957).

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Effect of Interference between Resonance and Potential Scattering on Resonance Absorption

In many recent calculations (*1*) of resonance integrals, use has been made of the narrow resonance (NR) and infinite mass (IM or NRIA) approximations, where the choice between the approximations has been based upon whether the practical width of the resonance is narrow or wide compared to the maximum energy loss of a neutron scattered from the resonance. For resonances having a practical width comparable to the maximum neutron energy loss, it has been recognized that the two approximations may disagree by a factor two or more and recent efforts have been made to obtain more accurate theories for such cases. Thus Chernick *et al.*, (*2*) have iterated the first order NR and IM approximations and Goldstein and Cohen (*3*), Bell and Bodine (*4*) have considered more general iterative and variational methods to connect the NR and IM limits.

In many of these theories either no account has been taken of the interference between resonance and potential scattering or it has been treated only very approximately. Recently, however, Rothenstein and Chernick (*5*) have shown that for absorption in a particular Bi lattice the interference is an important effect which increases absorption by about 40%. It is the purpose of this note to point out the general importance of interference for all resonances which are non-narrow (i.e., practical width $\gtrsim 4E/A$) and have appreciable scattering ($\Gamma_n \gtrsim \Gamma_a$). In general, for quantitative calculations of absorption in such resonances, the interference must be taken into account.

The effect on resonance absorption of interference between resonance and potential scattering can be seen most simply from numerical solutions of the integral equation for the neutron flux in an infinite homogeneous medium. The results of such calculations are given below for some U^{238} unbroadened Breit Wigner resonances and a Bi resonance with hydrogen as a moderator. In each case the resonance absorption probability was calculated both with and without interference and the results are compared.

Other calculations also show the importance of interference. Rothenstein (*6*) has evaluated the correction for narrow resonances and small interference. For fairly wide resonances and arbitrary interference, results may be obtained by iterative or variational techniques (*3*, *4*). For unbroadened Breit Wigner resonances, we have obtained analytic results with an approximate variational calculation. In these, the inclusion of interference increases the complexity of the calculation considerably and generalization to Doppler Broadened resonances may not be practical. Our variational results are compared with the numerical integration in Table I. The calculation used a flux trial function similar to that of Goldstein and Cohen (*3*), and a corresponding adjoint trial function. These were inserted into a Schwinger variational integral (*7*) for the neutron absorption and the resulting integrals evaluated. For the results reported here, the extremum was not found. Instead values of the parameters were chosen which simplified the result and were usually not far from the extremum. At any rate, errors in the absorption are of second order in the trial function errors.

Results for some strongly scattering U^{238} resonances in a 1:1 H/U mixture are summarized in Table I. For these calculations, Γ_γ = 0.025 ev, σ_p = 10 *b*, and σ_h = 20 *b*. It is

TABLE I

CAPTURE PROBABILITIES IN 1:1 H/U MIXTURE (T = 0)

Resonance energy	66.3	103.5 ev	192 ev
Resonance width, Γ	0.050 ev	0.092 ev	0.165 ev
Capture probability			
Numerical, no interference	0.0246	0.0179	0.00797
Numerical, with interference	0.0294	0.0228	0.01077
Variational, no interference	0.0249	0.0183	0.00813
Variational, with interference	0.0301		0.01072
NR, with interference	0.0226	0.0140	0.00597
NRIA or IM	0.0261	0.0219	0.01246
Numerical $\frac{\text{interference}}{\text{no interference}}$	1.20	1.27	1.35

TABLE II

CAPTURE PROBABILITY IN 103.5 EV U^{238} RESONANCE; σ_H = HYDROGEN CROSS SECTION PER URANIUM ATOM, INTEGRATION FROM 73 EV TO 147 EV

σ_H (barns)	Capture probability		
	No interference	With interference	Ratio
0	0.853	0.996	1.17
10	0.0265	0.0358	1.35
20	0.0176	0.0224	1.27
40	0.0116	0.0143	1.21
80	0.00766	0.00883	1.15
200	0.00444	0.00485	1.09
800	0.00197	0.00205	1.04
2000	0.00115	0.00118	1.02

seen that the effect of interference is to increase the absorption by from 20% to 35%. For a $\frac{1}{2}$:1 H/Bi mixture, interference increased absorption in the main Bi resonance (E_n = 784 ev, $\Gamma_\gamma/\Gamma \simeq 0.01$ and $g = 0.55$) by 32%. In Table II, the effect of varying hydrogen dilution is shown for the 103.5 ev U^{238} resonance. Evidently the importance of interference decreases as the uranium is diluted by additional hydrogen. All of these results were obtained at zero temperature. However it can be shown that the effect of interference will be similar at even, say 300°C.

The main physical reason why interference is important for these resonances is as follows: For the resonances in question, the effect of interference is always to increase the scattering for energies above the resonance peak and to decrease it below the resonance peak. Thus the effect is to increase scattering of neutrons into the resonance and to decrease scattering out and interference thus tends to trap the neutrons in the energy region of the resonance. To verify this, we have made one calculation in which the sign of the interference term was changed, thus giving constructive interference for energies below the resonance and destructive interference above. For this case (103.5-ev resonance and σ_h = 20) the capture was only 81% of that with no interference.

Evidently Doppler broadening will tend to decrease the effect of interference. Thus interference will give a contribution to the temperature coefficient which is opposite in sign to the usual Doppler coefficient (*6*).

The numerical integrations were performed with a code written for the IBM 704 by Mrs. J. Rudnick and the variational expressions were evaluated by Mrs. J. Powers.

REFERENCES

1. A. R. VERNON, Calculation of the effective resonance integral of U^{238}. *Nuclear Sci. and Eng.* **7**, 252 (1960); see also L. W. NORDHEIM, Theory of resonance absorption. Rept. GA-638 (1960) for further references.
2. J. CHERNICK AND R. VERNON, Some refinements in the calculation of resonance integrals. *Nuclear Sci. and Eng.* **4**, 649 (1958).
3. R. GOLDSTEIN AND E. R. COHEN, Neutron resonance absorption integrals. *Trans. Am. Nuclear Soc.* **3**, 232 (1960).
4. G. I. BELL AND A. BODINE (unpublished).
5. W. ROTHENSTEIN AND J. CHERNICK, Resonance absorption of neutrons in nonheavy absorbers. *Nuclear Sci. and Eng.* **7**, 454 (1960).
6. W. ROTHENSTEIN, Collision probabilities and resonance integrals for lattices, *Nuclear Sci. and Eng.* **7**, 162 (1960).
7. N. C. FRANCIS, J. C. STEWART, L. S. BOHL, AND T. J. KRIEGER., Variational solutions of the transport equation. *Proc. 2nd Intern. Conf. Peaceful Uses Atomic Energy, Geneva* **16**, 517 (1958).

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FNR Shim-Safety Rod Deformations

In August, 1960, the Ford Nuclear Reactor at the Phoenix Memorial Laboratory of The University of Michigan experienced a deformation of one of the three shim-safety rods installed in the reactor. The incident was discovered when this rod could not be withdrawn by normal procedures during a routine startup operation. Upon investigation it was found that this rod had swelled sufficiently to cause jamming in the special fuel element.

The shim-safety rods used on the FNR are flattened aluminum tubes fitted with appropriate endpieces and filled with boron carbide powder. These shim-safety rods are housed in MTR type fuel elements with an appropriate