# Thermal Neutron Absorption Cross Section of Deuterium

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The absorption cross section of deuterium for 2200-m/sec neutrons has been related to that of boron by intercomparison with lithium. A value of 0.57±0.01 millibarn for deuterium, based on a measured value of 755 barns for boron, has been obtained.

## I. INTRODUCTION

THE absorption cross section of deuterium has been reported[1] to be $0.46\pm0.11\times10^{-27}$ cm$^2$ for 2200-m/sec neutrons. This value is based on a measurement of the diffusion length in heavy water and the assumption that the absorption in oxygen is negligible. Since this quantity has considerable theoretical interest[2,3] and practical importance, the determination of a more accurate value has been undertaken. The method used is essentially a refinement of one devised by Langsdorf[4] in 1943. The production of tritium from deuterium by neutron irradiation is compared with that from lithium; the neutron absorption of the lithium is in turn compared with that of a boron standard. Since these comparisons can be made with high precision, the calculated cross section of deuterium is as reliable as that of the boron standard.

## II. EXPERIMENTAL PROCEDURE

Reagent grade lithium sulfate, dried to constant weight at 210°, was dissolved in specially purified heavy water, 99.57 percent D, to give a solution containing 0.937 gram atom of lithium per liter. The total cross section of this lithium solution was determined by comparison with standard boron solutions in a danger coefficient measurement[5] in the Argonne graphite reactor. The boron standards were prepared by diluting a heavy water solution of boric anhydride, the absorption cross section of which had been determined[6] by neutron transmission measurements.

TABLE I. Tritium formation in heavy water and lithium.

| Content of ampoule | Shield | Tritium $10^{14}$ amp mmol$^{-1}$ | $10^6\,\sigma_D/\sigma_{Li}$ |
|---|---|---|---|
| $D_2O$ | Cd | 0.100 | |
| $D_2O$ | Cd | 0.089 | |
| $D_2O$ | none | 7.74±0.05 | |
| $D_2O$ | none | 7.60±0.02 | |
| $Li_2SO_4$ 0.001871$N$ | none | 23.76±0.02 | 8.05 |
| $Li_2SO_4$ 0.003734$N$ | none | 40.07±0.04 | 7.98 |

One-gram samples of the heavy water and of two dilutions of the lithium sulfate solution in heavy water were weighed into quartz ampoules fitted with break seals. The ampoules were cooled in liquid nitrogen, evacuated, and sealed off. Two heavy water samples and the lithium solutions were irradiated in the vertical thimble of the Argonne heavy water reactor. Two ampoules of heavy water were wrapped in cadmium foil and similarly irradiated. Several days after removal from the pile each ampoule was opened on the vacuum line, the noncondensable gas was collected, the water was distilled, and aliquots of the distillate were converted to hydrogen by reaction with heated zinc. The tritium content of each hydrogen sample was determined by measurement, with a vibrating reed electrometer, of the current in an ionization chamber filled to atmospheric pressure with hydrogen.

## III. RESULTS AND DISCUSSION

Analyses of the irradiated samples are presented in Table I. The recorded specific activities include the tritium found in the noncondensable gas; in no sample did this account for more than 0.6 percent of the total tritium. The ratio of the atomic cross sections for tritium production is calculated from the formula

$$\sigma_D/\sigma_{Li}=T_D N_{Li}/(T_{Li}-T_D)N_D,$$

where $T_D$ and $T_{Li}$ are the concentrations of tritium found in the heavy water and in the lithium solution, respectively, $N_{Li}$ is the normality of the lithium solution at 25°, and $N_D$, the gram atoms of deuterium per liter of the heavy water, is 110.77 at 25°. No correction is made for the production of tritium by fast neutron capture since the tritium found in the cadmium-shielded samples can be accounted for by thermalization of epi-cadmium neutrons in the heavy water. The mean value of the ratio $8.02\times10^{-6}$ is probably accurate to ±1.5 percent.

The absorption of the boron standard corresponds to a cross section[6] of 755±5 barns per atom for 2200-m/sec neutrons. From the danger coefficient measurement, the ratio of the cross section of lithium to that of the boron is 0.0941±0.0006, after a small correction for the absorption[7] by sulfur. These values give a total absorption cross section of 71.0±0.7 barns for lithium. This is essentially equal to the cross section for tritium

[1] Sargent, Cavanagh, and Niemi, Can. J. Research **A25**, 134 (1947).
[2] E. H. S. Burhop and H. S. W. Massey, Proc. Roy. Soc. (London) **A192**, 156 (1947).
[3] N. Austern, Phys. Rev. **83**, 672 (1951); **85**, 147 (1952).
[4] A. Langsdorf, private communication.
[5] Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. **72**, 16 (1947).
[6] G. R. Ringo (to be published).
[7] *Nuclear Data*, National Bureau of Standards Circular No. 499 (1950), p. 28.

production by the $(n,\alpha)$ reaction, since the $(n,\gamma)$ cross section[8] of $Li^7$ is only 0.03 barn and that[9] of $Li^6$ in the natural element is less than 0.1 barn. Since boron, lithium, and deuterium are all $1/v$ absorbers, the cross section of deuterium for 2200-m/sec neutrons can be calculated to be $0.57\pm0.01$ millibarn.

[8] See reference 7, p. 4.
[9] B. Hamermesh and V. Hummel, Argonne National Laboratory (private communication).

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# Resonance in Collision Processes*

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The limitations are investigated under which "resonance" provides certain collision processes with preferred probability. In impacts of the second kind, resonance strongly affects the transfer of electronic into electronic energy or into a small amount of vibrational energy, possibly the transfer of vibration into vibration, certainly not the transfer of vibration into rotation. Resonance is not effective in the transfer of energy of atomic recombination into electronic energy and, in general, resonance is not effective in processes in which nuclei change positions by appreciable amounts.

## I. INTRODUCTION

IN certain cases impacts of the second kind show a preferred probability which Franck has attributed to "resonance." A similar preference due to "resonance" has been claimed for numerous other processes, in some instances with, in others without justification. In particular, certain theories of the afterglow of nitrogen, that is, of "active nitrogen," encounter difficulties by over-emphasizing the principle of resonance which actually applies only to a limited group of processes. The present paper proposes to examine the limits within which this principle is valid.

## II. RESONANCE

We consider collision processes in which energy is transferred from one quantized energy level to another in atoms or molecules. Impacts of the second kind are an important type. In certain instances a particularly large probability for the transfer of energy has been observed. Franck[1] described such cases by adopting the principle that the cross section of the process is large *if no energy or only little energy is changed into translation or received from translation.* A striking example of this condition, which is called "resonance," is given by the observation of Beutler and Josephy[2] that excited mercury atoms Hg′ transfer energy to Na atoms with a pronounced preference to the Na level with an energy closest to that of Hg′. Fluorescence of Na provides another example. When one of the *D* lines of Na is separately excited, the other *D* line appears, depending upon the pressure, presumably excited by impacts of the second kind. Manley and Duffendack[3] observed resonance in the simultaneous ionization and excitation of magnesium atoms caused by impacts of the second kind with metastable or ionized neon atoms.

The corresponding effect in the energy transfer from an atom, argon, to a diatomic molecule, hydrogen, was observed by Lyman and later interpreted by Dieke and Hopfield.[4] A hypothetical, more extreme process illustrating such cases is the excitation of the $O_2$ molecule, for which the potential curves are well explored. While the energy of dissociation of $O_2$ is 5.08 ev, the molecule readily absorbs light of greater energy in a continuous range leading to excited molecules in a state of such compression that the molecule immediately dissociates. There is little doubt that the $O_2$ molecule may receive the same amount of energy by an impact of the second kind from an atom endowed with, say, 6 ev energy of excitation. Again a preferred probability due to resonance is expected to govern this transfer of electronic energy, irrespective of the fact that ultimately the free atoms produced are given energy of translation.

Mott and Massey[5] discuss the theory of the resonance effect and conclude that the sharpest resonance is expected for transfer of excitation involving optically allowed transitions in both systems.

An additional rule governing the probabilities of impacts of the second kind, derived by Wigner[6] on the

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[1] J. Franck and P. Jordan, *Anregung von Quantensprüngen durch Stösse* (Springer, Berlin, 1926), p. 226.
[2] H. Beutler and B. Josephy, Z. Physik **53**, 747 (1929). See H. Beutler, Z. Physik **50**, 581 (1928).
[3] J. H. Manley and O. S. Duffendack, Phys. Rev. **47**, 56 (1935).
[4] T. Lyman, *Spectroscopy of the Extreme Ultraviolet* (Longmans Green, New York, 1928), second edition, p. 91; G. H. Dieke and J. J. Hopfield, Phys. Rev. **30**, 414 (1927).
[5] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Clarendon Press, Oxford, 1949), second edition, p. 284. See P. M. Morse and E. C. G. Stueckelberg, Ann. Physik **9**, 579 (1931).
[6] E. Wigner, Gött. Nachr. 375 (1927). For the experimental confirmation, see A. C. G. Mitchell and M. W. Zemansky, *Resonance Radiation and Excited Atoms* (The Macmillan Company, New York, 1934), p. 69.