On the Angular Distribution of 3.1-Mev Neutrons Scattered by Protons

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THE angular distribution of the scattering of fast neutrons by protons has been usually studied by analyzing the recoil protons. Therefore, the results are concerned with the neutrons which are scattered backwards. They showed an isotropic distribution at the energy of *d–d* neutrons. On the other hand, the angular distribution in the forward direction has been studied by Kikuchi, Aoki, and Wakatsuki.[1] They used ring scatterers and an ionization chamber filled with methane or hydrogen gas at high pressure to detect the scattered neutrons. The peculiarity of this method is that it gives the absolute value of the differential scattering cross section. The values of the differential scattering cross sections at different angles thus obtained were equal to each other within the experimental error. But the absolute values were only about a half of $\sigma_0/4\pi$, where σ_0 is the total scattering cross section for the proton. If correct, the result indicated a strong asymmetry in the scattering. The experiment has been repeated, since by some improvements of the apparatus a larger intensity of neutrons became available and better geometric conditions could be used. We raised the sensitivity of detection by increasing the number of hydrogen atoms in the ionization chamber and by using more scattering materials. The other arrangements were almost the same as those used in the previous experiments. The monoenergetic neutrons used were from the *d–d* reaction and were produced in a thick heavy water ice target by an unanalyzed beam of 100μamp. of 300-kev. deuterium ions. The ring scatterers were of paraffin, graphite, water, quartz, and silicon.

We measured the ratio $\Delta I/I_0$, where ΔI is the increase of the ionization current in the ionization chamber when the ring scatterer was placed in position, and I_0 is the ionization current produced by neutrons coming directly from the target. We computed the scattering by a proton by subtracting the contribution of carbon and oxygen from the scattering of paraffin and water, respectively. In this case, we made the assumption that the ionization current in the ionization chamber produced by neutrons, which lost their energy through the collision with protons, was proportional to the product of the energy after collision and the total scattering cross section of neutrons at that energy. We used for the values of the total scattering cross section the data obtained by C. L. Bailey, *et al.*[2]

Our results are summarized in Table I and are shown in Fig. 1.

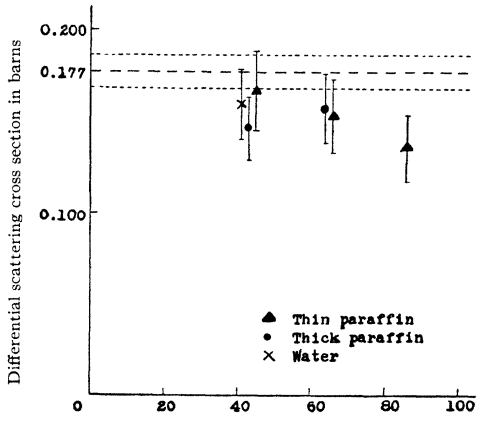

FIG. 1. Differential scattering cross section in c.m. system. Dotted line indicates $\sigma_0/4\pi$, where σ_0 is the total scattering cross section.

The errors involved in these values of the cross section came mainly from the errors involved in the total scattering cross section which was used in the calculation of the sensitivity of the ionization chamber. From these results we conclude that the angular distribution in the forward direction is consistent with isotropic scattering. The cause of the discrepancy with the former results is not clear.

TABLE I. The differential scattering cross section of 3.1-Mev neutrons scattered by protons in the center-of-mass system.

Scattering angle in c.m. system in deg.	Scatterer and its weight in grams	$(\Delta I/I_0)_{\text{proton}}$ in %	Differential cross section in c.m. system in barns
44±10	Paraffin 50.7	2.19±0.07	0.166±0.022
	Paraffin 94.9	3.10±0.05	0.146±0.017
	Water 94.1	2.32±0.06	0.159±0.019
66±10	Paraffin 71.8	2.06±0.06	0.153±0.020
	Paraffin 141.4	3.38±0.07	0.157±0.019
86±10	Paraffin 95.4	1.63±0.06	0.136±0.019

Total cross section $\sigma_0/4\pi = 0.177 \pm 0.009$ barn

We wish to express our gratitude to Professors S. Kikuchi and T. Wakatsuki for their advice and encouragement throughout the progress of this work.

[1] Kikuchi, Aoki, and Wakatsuki, Proc. Phys. Math. Soc. Japan **21**, 410 (1939); T. Wakatsuki, Proc. Phys. Math. Soc. Japan **22**, 430 (1940).
[2] C. L. Bailey, *et al.*, Phys. Rev. **70**, 583 (1946).

Infra-Red Absorption of Hydrogen Induced by Foreign Gases

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THE vibrations of O_2, N_2, and H_2, and the symmetrical mode of CO_2, all normally inactive in infra-red absorption, are rendered active by intermolecular forces in the compressed gas.[1] The absorption was attributed to the dipole moment arising from the distortion of the charge distribution of the absorbing molecule during a collision. This interpretation is substantiated by the effect of foreign gases added to the absorbing gas; N_2 added to O_2, N_2 and He to H_2. More complete data on the absorption induced in H_2 by He, A, and N_2 are presented here.

Hydrogen at a given pressure was admitted to the cell, 85 cm in length, and the foreign gas added at partial pressures up to 100 atmospheres. Several partial pressures of hydrogen in the range 10 to 50 atmospheres were used. The enhancement due to the foreign gas was obtained by subtracting the absorption of the H_2 alone from the absorption of the mixture. Over the pressure ranges used the integrated absorption coefficient of the enhancement varies linearly with the product of the foreign gas density and the hydrogen density, and can therefore be expressed as a specific absorption coefficient. The specific absorption coefficients are given in Table I.

The effectiveness of He and A in increasing the induced absorption is of special significance. Mizushima[2] has interpreted the absorption observed in O_2 and H_2 in terms of the polarization of the absorbing molecule by the quadrupole fields of the surrounding molecules. Since the rare gas atoms possess no quadrupole field, the absorption induced by these atoms in H_2 cannot

TABLE I. Coefficient of induced absorption.

	(cm^{-1} $sec.^{-1}$ per molecule H_2) (per molecule foreign gas per cm^3)	(cm^{-1} $sec.^{-1}$ per atmos. H_2) (per atmos. foreign gas at 0°C)
H_2-He	0.0744×10^{-30}	0.00537×10^{10}
H_2-A	0.233×10^{-30}	0.0168×10^{10}
H_2-N_2	0.257×10^{-30}	0.0185×10^{10}
H_2-H_2	0.105×10^{-30}	0.00759×10^{10}

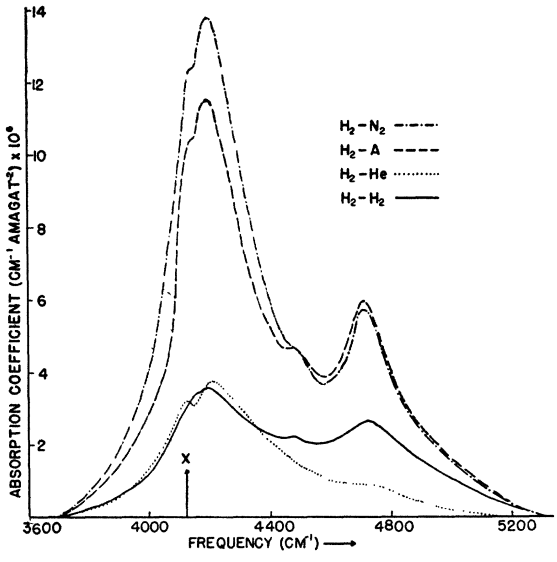

FIG. 1. Contours of the induced infra-red absorption of hydrogen.

be explained by the quadrupole field effect, and must be due to induction by close collisions. H_2 and N_2 have quadrupole moments, but the absorption in pure H_2 and in the H_2-N_2 mixture must also be mainly collision induced, since on hydrogen He is nearly as effective as H_2 and A is nearly as effective as N_2. The comparable intensities of the Q- and S-branches in H_2, N_2, and O_2 is further evidence that the quadrupole field effect is relatively unimportant. Mizushima's calculation predicts an intensity distribution similar to that in the Raman effect in which for these molecules the intensity of the Q-branch is many fold more intense than the other branches.

The contours of the absorption in H_2 induced by the foreign gases are reproduced in Fig. 1. For A and N_2 the $S(0)$ and $S(1)$ rotational lines are quite prominent, but for He they are appreciably weaker relative to the Q-branch. A contour for pure H_2 is shown for comparison. The frequency calibration, obtained with Edser-Butler fringes,[3] is more accurate than that for the previously published contour.[1] It is now evident that the frequency of the peak of the Q-branch for pure H_2 and for each mixture is 40 to 50 cm^{-1} higher than the vibrational frequency of the free molecule. All contours show a weak sharper component marked X; it is barely apparent in the H_2 contour in Fig. 1, but is more prominent at higher densities. This component cannot be assigned to the rotational fine structure of the band, and as yet its origin is speculative.

The large half-width of the rotational lines, about 320 cm^{-1} at room temperature, is a notable feature of the induced absorption of H_2. This indicates that the duration of the perturbation is short, and hence that close collisions are causative. The induced absorption of H_2 cooled by liquid air has been recorded, and the half-width of the lines is markedly reduced. The half-width appears to be proportional to the square root of the absolute temperature, and thus proportional to the thermal velocity. This dependence further confirms the hypothesis that the absorption in H_2 is caused by a dipole moment induced mainly by the overlap forces operative during a close two-body collision.

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[1] Crawford, Welsh, and Locke, Phys. Rev. **75**, 1607 (1949). Welsh, Crawford, and Locke, Phys. Rev. **76**, 580 (1949).

[2] M. Mizushima, Phys. Rev. **76**, 1268 (1949).

[3] W. Ewart Williams, *Applications of Interferometry* (Methuen and Company, Ltd., London, 1930), p. 101.

Excitation Function of the Reaction $C^{12}(\gamma,p)B^{11}$

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IT is the purpose of this note to describe a measurement of the yield curve of the reaction $C^{12}(\gamma,p)B^{11}$, using the University of Pennsylvania 25-Mev betatron. The data of this experiment when combined with knowledge of the incident photon energy spectrum permit the calculation of the absolute total cross section of the reaction as a function of energy.

The arrangement of the apparatus employed in the experiment is shown in Fig. 1. The collimated x-ray beam has an angular divergence of 0.22 degree. The cross section of the beam at the target position is a sharply defined circle $\frac{9}{32}$ in. in diameter. The target is a slab of graphite approximately one sq. in. in area and 38 mg-cm^2 thick, placed such that the target surface makes an angle of 30° with the x-ray beam. The proton detectors are scintillation counters each of which consists of an RCA 5819 phototube, a silver activated ZnS screen supported in a vertical plane by 0.1 cm thick glass backing, and a hemispherical aluminum reflector in which there is a thin (0.00035-in. aluminum) window to permit the entrance of photo-protons. The area of the ZnS screen is 1 cm^2. Since the scattering chamber is not evacuated, protons emitted from the target traverse approximately 7.3 cm of air before striking the detector screen. The two scintillation counters are operated independently. The output pulses from each of the photo-tubes are fed into separate cathode followers, amplifiers, discriminators, and scaling circuits, all of conventional design.

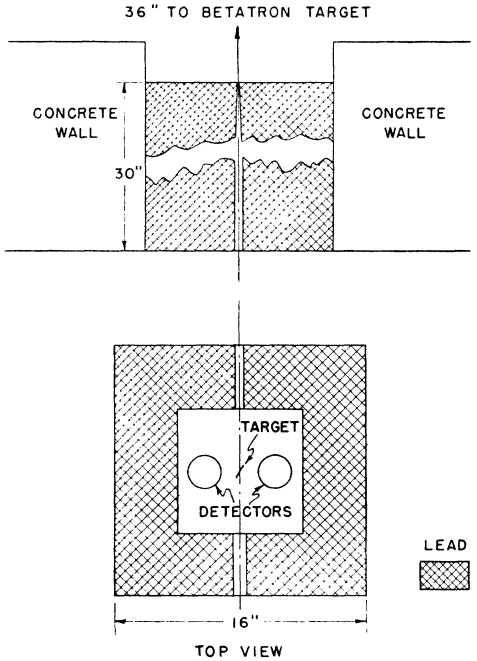

FIG. 1. General arrangement of apparatus.

The data of the experiment are a series of integral bias curves, each curve corresponding to a maximum energy of the x-ray beam. A direct comparison of the integral bias curves results in the yield curve which is shown in Fig. 2. It should be noted that the data in Fig. 2 were obtained using only one of the scintillation counters. The yield curve from the other counter is identical with that in Fig. 2 except for a 10 percent difference in the scale of the ordinate. This difference might easily result from a difference in the geometry of the two counters.

The approximate energy spectrum of the betatron x-ray beam