circles represent the values corrected for the fraction of the beam of protons that either missed the target or were scattered from it. The curve is a plot of the function $R=3\csc\theta$, where θ is the angle between the proton beam and the surface of the target.

Conclusion

The disagreement between the value of three obtained in the present experiment and that of four obtained by Schneider as the value of the secondary electron-proton ratio from thick targets perpendicular to the proton beam probably may be explained by a difference in the outgassing of the targets. If a very small proton current were used, the ratio would decrease very slowly with time and thus would remain near the value obtained when the metal was first exposed to the beam.

The high yield obtained from Be after a short heating is similar to the results obtained recently by Kollath[4] for Be bombarded by electrons. He investigated very carefully the effects of heating and oxidizing upon the secondary electron-primary electron ratio. The value of 0.5 or 0.6 obtained for this ratio from a freshly evaporated target was raised to about 5.5 when the target had been heated at a temperature of about 700 degrees centigrade for a few minutes in a good vacuum. The same results were obtained by heating the metal in an atmosphere of oxygen. Kollath attributed the increased yield not to the formation of a layer of oxide upon the surface, but to a change in the crystal structure of the surface.

The variation of the yield with the angle between the target and the proton beam may be explained at least qualitatively by assuming that the secondaries that are able to reach the surface are produced along a part of the proton path near the surface in the metal. Then the efficiency of the production of the secondaries will be constant for this very short distance. As the angle is decreased, more and more of the total path of the protons becomes effective in producing secondaries according to a csc θ law. This is true only if the penetration of the incident particles is much greater than that of the secondaries which is clearly true in the present case. Müller[5] gives a similar explanation for the angular dependence of the yield of the secondaries created by electrons having energies of a few thousand volts.

In conclusion, the author wishes to express his gratitude to Professor J. H. Williams for placing the facilities of the nuclear research laboratory at his disposal and for many helpful discussions during the course of this investigation.

[4] R. Kollath, Ann. d. Physik **33**, 285 (1938).

[5] H. Müller, Zeits. f. Physik **104**, 475 (1937).

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The Scattering of Slow Neutrons by Gaseous Ortho- and Parahydrogen: Spin Dependence of the Neutron-Proton Force

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Room temperature and liquid-air neutrons have been scattered by gaseous ortho- and parahydrogen at 90°K. The results check with those of Brickwedde, Dunning, Hoge and Manley for liquid hydrogen if reasonable allowances are made for the Doppler effect of the motion of the scattering H_2 molecules.

I. Introduction

As Teller[1,2] has pointed out, the different orientations of the protons in ortho- and parahydrogen must affect the scattering of slow neutrons by these molecules if the neutron proton scattering is dependent on the relative orientations of the spins of the neutron and the proton. A second point is that the absolute magnitude of the elastic scattering cross sections must also

* Fellow of the Lalor Foundation, 1937–38.

[1] E. Teller, Phys. Rev. **49**, 420 (1936).

[2] J. Schwinger and E. Teller, Phys. Rev. **52**, 286 (1934).

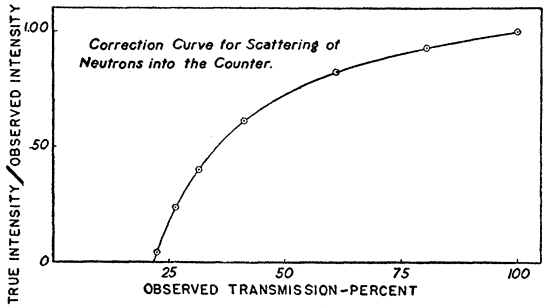

FIG. 1. Correction curve for scattering of neutrons into the counter.

depend very seriously on whether the singlet state (first excited state, and presumably mainly responsible for slow neutron scattering by protons) of the deuteron is real or virtual, i.e., has a positive or negative binding energy. Schwinger and Teller[2] have calculated the predicted cross sections in detail for the case of the virtual level and have clearly indicated how those for the real level are to be obtained.

Though the results of Halpern, Estermann, Simpson and Stern[3] and of Brickwedde, Dunning, Hoge and Manley[4] on the scattering by liquid hydrogen showed that the scattering was spin dependent and indicated that the singlet state was virtual, it seemed desirable to perform the experiment in the gaseous state, where intermolecular liquid forces could hardly enter. The theoretical calculations[2] had been made for gaseous hydrogen molecules with negligible velocity along the neutron beams. It was necessary, therefore, to keep the gas as cool as possible in order that the motion of the scattering molecules would not smooth out the predicted results of changing neutron temperature to unobservably small values. There was the additional consideration that the parahydrogen had been supposed to be entirely in the ground rotational state ($J=0$). This required that the temperature be no higher than 90°K.

II. Apparatus and Method

The scattering gas was contained in a cylindrical copper bomb ten cm in diameter and twenty-five cm long. The wall was one millimeter thick. On the surface of the bomb were soldered two flat coils of copper tubing, so placed as not to obstruct the neutron beam. Liquid air was circulated through this tubing to keep the gas at 90°K. A pressure line connected the bomb to the storage hydrogen tank and a calibrated pressure gauge. The temperature of the gas in the bomb was measured by observing the pressure increase on warming to room temperature. It averaged within two or three degrees of 90°K.

The neutron detector was a BF_3 counter[5] (in one case five of them working in parallel) of conventional design. The source of neutrons was two hundred milligrams of radium as bromide mixed with about ten grams of powdered beryllium metal and placed in a sealed steel tube. For the work with room temperature neutrons a paraffin "howitzer" was used. The "liquid-air" neutrons were obtained through the walls of a metal Dewar vessel containing a cylinder of paraffin immersed in liquid air and surrounding the radium source. The boron absorption coefficient of the neutrons was carefully measured and found to have the value of 1.55 ± 0.05 times the value for neutrons from room temperature paraffin. This corresponds to a neutron temperature[5] of $125°\pm10°$K. This value for the ratio of the boron absorption coefficients of liquid-air and room temperature neutrons has been reported frequently in the literature with good agreement among the values. The neutron temperature given by the method certainly is most reasonable.

The parahydrogen gas was made by placing a few hundred cc of carefully pumped charcoal in about eight liters of liquid normal hydrogen in a Pyrex Dewar surrounded by a metal can and a bath of liquid air. Conversion was then allowed to occur for a period of about twenty-four hours until the composition was pure *para* within one or two percent (as shown by analysis of samples of the gas over the liquid). This left about two and one-half liters of liquid, which was then evaporated into a large oil-filled gas holder by means of a heater coil. The hydrogen compressor was then used to transfer the parahydrogen to a twenty-cubic-foot steel cylinder at a pressure of about one hundred atmospheres. The gas was immediately transferred to the

[3] J. Halpern, I. Estermann, O. C. Simpson and O. Stern, Phys. Rev. **52**, 142 (1937).
[4] F. G. Brickwedde, J. R. Dunning, H. J. Hoge and J. H. Manley, Phys. Rev. **54**, 266 (1938).
[5] W. F. Libby and E. A. Long, Phys. Rev. **52**, 592 (1937).

copper bomb and the experiment started. Samples of the gas were taken at the beginning and at the end of all runs, but in no case was the conversion in the copper bomb measurable during the three or four hours required for each run. It was found that the compressor did not convert the gas appreciably. It was necessary to flush the pressure lines free of normal hydrogen, of course, before transferring parahydrogen. The runs with parahydrogen were made with gas at least 98 percent *para* in most cases. The gas analyses were made by the heat conductivity method of Bonhoeffer.[6] Two entirely independent gauges were used and the analyses were checked by different observers. A further check was made by measuring the difference in vapor pressure of normal hydrogen and a particular sample of para-rich liquid at the boiling point of the latter. The result checked the heat conductivity analysis of the gas. The authors believe the compositions were good to one or two percent.

The apparatus was arranged so the distances from the scatterer to the source and to the counter were each about twenty-five cm. The cross-sectional area of the neutron beam at the source was about one hundred square cm. The counter was 2.3 cm in diameter and 13 cm long. The whole neutron beam was protected and defined in all directions by cadmium sheets. A cadmium sheet (1 mm thick) served as shutter between the source and scatterer. It was necessary to surround the copper bomb with a tinned iron box to prevent the collection of snow and ice on the bomb. (The hydrogen in the ice would have scattered neutrons.) This box was lined with cadmium except for two windows defining the beam. These windows were kept free of ice by means of warm air blasts and periodic heating.

Because of the finite size of the scatterer and the necessarily relatively short distances between it, the source, and the counter, it was necessary to make a correction for the scattering into the counter of neutrons which would have missed it if the scatterer had not been present. This correction, shown in Fig. 1, was calculated graphically from the dimensions of the apparatus on the assumption of isotropic scattering, and was checked experimentally by measuring the scattering cross sections of the gases ethane, ethylene, and methane in the apparatus. Presumably the scattering cross section of the protons in ethane should be nearly the same as the value for the protons in paraffin, paper, etc. It was found that the use of the data of state for ethane[7] and the above correction curve gave a logarithmic transmission curve (within the limits of error) corresponding to a cross section of $46\pm3\times10^{-24}$ cm^2 per proton for room temperature neutrons after the known value for carbon had been subtracted. This is in approximate agreement with the values for paraffin, etc. Ethylene gave the same value and methane gave $36\pm4\times10^{-24}$ cm^2. The corrections to the transmissions are serious for transmissions of fifty percent or less, but the authors believe it to be unlikely that the corrections should introduce

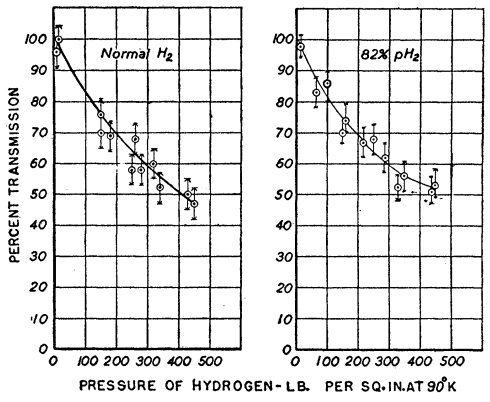

FIG. 2. FIG. 3.

FIGS. 2 and 3. Data for room temperature neutrons and normal H_2 (Fig. 2); 82 percent *para* H_2 (Fig. 3).

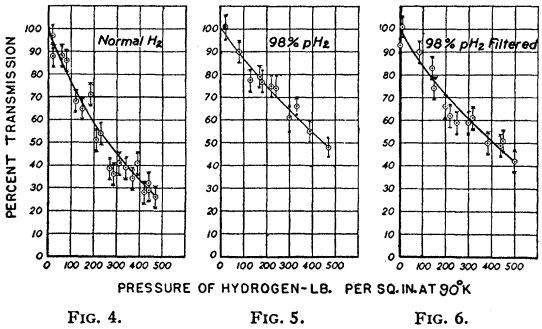

FIG. 4. FIG. 5. FIG. 6.

FIGS. 4, 5, and 6. Data for liquid-air neutrons and normal H_2 (Fig. 4); 98 percent *para* H_2 (Fig. 5); 98 percent *para* H_2 (Fig. 6) after filtering out 50 percent of beam with 98 percent *para* H_2.

[6] A. Farkas, *Orthohydrogen, Parahydrogen and Heavy Hydrogen* (Cambridge University Press, 1935), p. 23.

[7] B. H. Sage, D. C. Webster and W. N. Lacey, Ind. Eng. Chem. **29**, 658 (1937).

more than about five percent error in the absolute value of the cross sections providing the scattering by the hydrogen molecules is approximately isotropic, as it is expected to be.

From the theoretical work[2] it is clear that if the singlet state of the deuteron is virtual, filtering out fifty percent of a beam of liquid-air neutrons with parahydrogen gas at 90°K should result in a reduction in the scattering cross section of parahydrogen for the residual fifty percent. In order to test this point two bombs identical with the one described above were arranged in series in the neutron beam. The first was filled with parahydrogen gas till the beam intensity had fallen to about half-value and the scattering curve was then run with the second bomb. The distances were such that the scattering correction was the same as with the single bomb arrangement. (This point was checked both by calculation and by direct measurement with ethane.) The single counter was replaced by five like it working in parallel to increase the sensitivity.

Results

Figures 2–6 are from the data for scattering experiments done under the conditions indicated in each case. Figs. 2 and 3 are for room temperature neutrons, Figs. 4 and 5 for liquid-air neutrons, and Figs. 5 and 6 show the results of filtering the liquid-air neutron beam with parahydrogen gas at 90°K on the scattering by parahydrogen. Fig. 5 is for the unfiltered beam and Fig. 6 for the filtered beam. The errors indicated in the figures are about one and one-half times larger than the probable errors of counting.

The absolute cross sections were calculated from these data by first converting the pressures into the number of molecules of H_2 in the beam by use of the perfect gas laws and the thickness of the bomb. Correction was then made for scattering of neutrons into the counter which would have missed the counter had the scattering gas been absent. This was done according to Fig. 1. Each point was then plotted on a plot of logarithm of intensity against number of molecules in the beam and the best straight line drawn. The errors for the cross sections were obtained by consideration of the scattering of the points on this plot and are standard deviations.

Table I. *Cross section of protons in* H_2.

Experimental Conditions	Cross Section per Proton ($\times 10^{24}$ cm)	Results of Brickwedde, Dunning Hoge and Manley[4]
Para H_2 300° neutrons	22±4	15
Ortho H_2 300° neutrons	22±4	28
Para H_2 130° neutrons	19±4	9
Ortho H_2 130° neutrons	39±5	39

Table I shows the four different cross sections obtained from the data together with those of Brickwedde, Dunning, Hoge and Manley[4] obtained with liquid hydrogen.

Comparison of the results with those of Brickwedde, Dunning, Hoge and Manley[4] for liquid hydrogen shows that instead of a fourfold ratio of *ortho* to *para* cross sections for liquid-air neutrons the gas gives a twofold ratio. The authors believe that this can be understood on the basis of the Doppler effect of the motion of the H_2 molecules along the neutron beam direction. (Calculation of this effect with a 130°K Maxwellian neutron velocity distribution and the theoretical curves given by Schwinger and Teller[2] for the variation of the various cross sections with relative velocity of the neutron and the H_2 molecule bears this out more or less quantitatively.)

Of course there is the additional point that the neutrons used in this work may have been somewhat warmer than those used in the work with the liquid. This would cause the *ortho* and *para* cross sections to differ less than they would have with colder neutrons. However, it seems unlikely that this effect could have been large enough to account for the main part of the difference between the two experiments. The whole problem is seriously complicated, in both cases, by the presence of the high energy neutrons which are absorbed by the cadmium shutter but are still much above the energies for which the theoretical calculations apply. It seems to be necessary to eliminate these neutrons before the best results can be obtained from the experiment.

The failure to observe a decrease in parahydrogen cross section on filtering is not contradictory to the results obtained for the liquid because the errors in the gas work are large enough to have masked an effect of the size

found in the liquid. However, the data do show that the filtration effect for gaseous hydrogen is not much larger than that found for the liquid.

In general, the results check the liquid work and show no evidence of serious interference of liquid forces in the scattering phenomena. The difference between the scattering cross sections for ortho- and parahydrogen appear to be large enough to establish definitely a spin dependence of the neutron proton force.

The authors are grateful to Professor Gilbert N. Lewis for the suggestion that a gaseous scatterer be used and for helpful criticism in general. They also are indebted to Professor J. R. Oppenheimer, Dr. Willis E. Lamb, and Dr. L. I. Schiff of the Physics Department and to both Professor Felix Bloch of Stanford University and Professor Enrico Fermi of the University of Rome for advice concerning theoretical aspects of the problem.

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Atomic Electron Velocities in Nitrogen and Methane

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When sufficiently fast electrons are scattered by gas atoms it can be shown that the *distribution of energies* among the inelastically scattered electrons has exactly the same shape as the *distribution of component velocities* among the atomic electrons. An experimental determination of the distribution of energies among the electrons scattered inelastically by nitrogen and methane has been made. From these results the distributions of component velocities among the atomic electrons in nitrogen and methane have been computed. Half of the electrons have component velocities less than 1.80×10^7 cm/sec. in nitrogen, and less than 1.55×10^7 cm/sec. in methane. The experimental results refer to the L electrons only, as the apparatus would not permit the use of electrons of high enough energy to give the same information about the K electrons. The experimentally determined distributions of component velocities among the atomic electrons for nitrogen and methane are decidedly flatter than the theoretical calculated distributions for atomic nitrogen and atomic carbon. No theoretical calculations are available for molecular nitrogen and methane, hence comparisons were made with the calculations for the atoms.

INTRODUCTION

MANY investigations, both theoretical and experimental, have been carried out during the last twenty years on the "atomic structure factor." The significance of the factor is that it gives us the probability of finding an electron at each point in the atom. A knowledge of the distribution of momenta among the electrons is complementary to this and is essential to a complete description of the state of the electrons in an atom. Whereas an immense amount of work has been done on the first distribution, that relating to the positions of the electrons, comparatively little has been accomplished in describing the momenta of the electrons. Since the mass of an electron does not depend appreciably on its velocity in the range with which we are concerned, we can use the term "atomic electron velocity" as equivalent to momentum insofar as we are interested in variations of these quantities. Information as to the distribution of atomic electron velocities has been obtained from a study of the profile of the modified band in the Compton effect.[1] A different method was devised later in which a study of the distribution of energies among the electrons scattered by a gas was used to give information about the velocities of atomic electrons.[2] When electrons of sufficient energy are scattered through an appreciable angle by a gas at low pressure it is possible to regard the process as resulting from

[1] P. A. Ross, Proc. Nat. Acad. Sci. **9**, 246 (1923); G. E. M. Jauncey, Phys. Rev. **25**, 314, 723 (1925); J. W. M. DuMond, Phys. Rev. **33**, 643 (1929); J. W. M. DuMond and H. A. Kirkpatrick, Phys. Rev. **37**, 136 (1931); **38**, 1094 (1931); J. W. M. DuMond and A. Hoyt, Phys. Rev. **37**, 1443 (1931); J. W. M. DuMond, Rev. Mod. Phys. **5**, 1 (1933); G. E. M. Jauncey, Phys. Rev. **46**, 667 (1934); J. W. M. DuMond and H. A. Kirkpatrick, Phys. Rev. **52**, 419 (1937); H. A. Kirkpatrick and J. W. M. DuMond, Phys. Rev. **54**, 802 (1938).

[2] A. L. Hughes and M. M. Mann, Jr., Phys. Rev. **53**, 50 (1938). A. L. Hughes and M. A. Starr, Phys. Rev. **54**, 189 (1938).