were reduced by excess scattering of faster neutrons in parahydrogen. The theoretical implications of these data will be discussed in a companion note by Dr. Schwinger. We had planned to repeat the work, to improve the statistical accuracy and to search for possible systematic errors, but pressure of other work now makes that impossible for some time.

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Neutron Scattering in Ortho- and Parahydrogen and the Range of Nuclear Forces

Experiments on slow neutron scattering in ortho- and parahydrogen[1] have proved useful in distinguishing between the alternative possibilities of a real or a "virtual" singlet state of the deuteron. It is the purpose of this note to stress that experiments of the nature described by Alvarez and Pitzer[2] provide invaluable information concerning the neutron-proton interaction in the triplet state, in particular the effective range of the forces. The information ultimately available from such investigations is embodied in values for the singlet and triplet scattering amplitudes a_0 and a_1, which are related to the corresponding cross section, σ_0 and σ_1, by $\sigma_{0,1}=4\pi a_{0,1}^2$. The sign of a_0 relative to that of a_1 is the experimental criterion for the nature of the singlet state. That the relative sign is negative is the essential result of previous investigation. The magnitude of a_0 coupled with a detailed assumption concerning the range and shape of the singlet interaction potential serves to determine the magnitude of the interaction energy. The magnitude of a_1 and the triplet binding energy will determine both magnitude and range of the triplet interaction energy with a definite assumption concerning the shape of the interaction potential. Thus the essence of the investigation is an accurate determination of the triplet scattering amplitude.

The transition cross sections among the various levels of the hydrogen molecule involve different combinations of a_1 and a_0. The cross sections for transitions among the para-levels are proportional to $(3a_1+a_0)^2$, transitions among the ortho-levels are proportional to the combination $(3a_1+a_0)^2+2(a_1-a_0)^2$, while transitions between the ortho- and para-level systems involve $(a_1-a_0)^2$. Only the quantity $(3a_1+a_0)^2$ is sensitive to the precise numerical value of a_1, for a_0 is large and of opposite sign compared to $a_1(a_0/a_1\sim-4)$. Parahydrogen at the low temperatures required for the nonexcitation of rotational levels, irradiated by neutrons of energy insufficient for excitation is therefore the experimental medium appropriate to the determination of this quantity; for this enables one to measure the elastic scattering cross section of parahydrogen in its ground rotational level, free from contamination by other, large, cross sections, save for the small capture cross section. To avoid the disturbing influence of molecular binding forces, it is necessary to use molecular hydrogen in the gaseous phase. This, however, introduces a complication occasioned by the large thermal motion of the molecules. If the target molecules are not stationary, but possess a distribution in the molecular velocity $\mathbf{u}$, the effective cross section for a neutron of velocity $\mathbf{v}$, $\sigma_{\text{eff}}(\mathbf{v})$, is not the usual cross section $\sigma(\mathbf{v})$, but rather

$$\sigma_{\text{eff}}(\mathbf{v})=\frac{1}{v}\int|\mathbf{v}-\mathbf{u}|\,\sigma(\mathbf{v}-\mathbf{u})N(\mathbf{u})(d\mathbf{u}).$$

Here $N(\mathbf{u})$, the molecular velocity distribution function, represents the Maxwellian distribution appropriate to the temperature of the gas, T. Thus, were the actual cross section independent of velocity,[3] the effective cross section would exhibit a velocity dependence represented by[4]

$$\sigma_{\text{eff}}(E)=\sigma\left\{\left(1+\frac{1}{2\xi^2}\right)\Phi(\xi)+\pi^{-\frac{1}{2}}\frac{1}{\xi}e^{-\xi^2}\right\},\quad \xi=(2E/kT)^{\frac{1}{2}}$$

considered as a function of the neutron energy E. Under the conditions employed by Alvarez and Pitzer ($E/k=T=20°\text{K}$), this yields $\sigma_{\text{eff}}=1.247\sigma$. The actual correction factor for parahydrogen will be only somewhat smaller, since the cross section decreases but slightly in the small energy range under consideration ($E=0.00173$ ev).

The cross section curves necessary for the evaluation of σ_{eff} have been computed by Schwinger and Teller,[5] with extensions and improvements by Hamermesh.[6] The effective cross section for the $0\to0$ rotational transition, the elastic scattering of para H_2, is simply

$$\sigma_{\text{para}}=\sigma_{0\to0}=6.473(3a_1+a_0)^2.$$

The cross section for scattering by orthohydrogen will consist additively of the elastic scattering cross section ($1\to1$) and the cross section for the inelastic process in which the molecule is converted to parahydrogen in its ground state ($1\to0$). For these, one obtains

$$\sigma_{1\to1}=6.291[(3a_1+a_0)^2+2(a_1-a_0)^2]$$
$$\sigma_{1\to0}=1.447(a_1-a_0)^2.$$

Combined with the experimental results of Alvarez and Pitzer,

$$\sigma_{\text{para}}=(5.2\pm0.6)\times10^{-24}\ \text{cm}^2,$$
$$\sigma_{\text{ortho}}=(100\pm3)\times10^{-24}\ \text{cm}^2,$$

these formulae imply that

$$(3a_1+a_0)^2=0.803\times10^{-24}\ \text{cm}^2,\quad (a_1-a_0)^2=6.77\times10^{-24}\ \text{cm}^2.$$

These equations have four sets of solutions but may, by the theoretical prediction that a_1 be of negative sign, be restricted to the two sets:

(I) $a_1=-4.26\times10^{-13}$ cm, $a_0=21.8\times10^{-13}$ cm,
(II) $a_1=-8.74\times10^{-13}$ cm, $a_0=17.3\times10^{-13}$ cm.

Had we used the lower limit of the experimental para cross

section (4.6×10^{-24} cm^2), the triplet amplitude of the first set would have been -4.49×10^{-13} cm. The theoretical triplet amplitude increases in magnitude with increasing range and has the value

$$-1/\alpha(=(\hbar^2/M|E_0|)^{\frac{1}{2}})=-4.37\times10^{-13}\text{ cm}$$

for zero range. Thus to within the statistical uncertainty of the observations the two admissible values of a_1 are (I) $a_1=-1/\alpha$, (II) $a_1=-2/\alpha$. These correspond, respectively, to (I): zero range, (II): a rectangular-well range $\sim8\times10^{-13}$ cm. Both values are theoretically untenable, the expected range being $\sim2.8\times10^{-13}$ cm. A further difficulty is revealed by computing the cross section for slow neutron scattering by free protons, *viz.:*

$$\tfrac{3}{4}\sigma_1+\tfrac{1}{4}\sigma_0,$$

which may be written

$$\tfrac{1}{4}\pi[(3a_1+a_0)^2+3(a_1-a_0)^2]=16.6\times10^{-24}\text{ cm}^2.$$

This result is considerably less than the directly measured value[7] of $(20\pm1)\times10^{-24}$ cm^2.

The consequences of these ortho-para measurements are at such complete variance with present theoretical concepts that it would be highly desirable to repeat these measurements and search for possible systematic errors.

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* This work was done while the author held a National Research Fellowship, 1939–1940.

Spectroscopically Pure Mercury (198)

For some time, spectroscopists in the national laboratories have been searching without much success for a line more nearly monochromatic than the red line of cadmium, to use as a standard of length. Professor W. E. Williams pointed out to us that if it were ever possible by some means to separate the isotopes of mercury, the green line λ5461 produced by one of the even isotopes would be admirably suited for the purpose. There would be no hyperfine structure, no isotope shift, and little Doppler broadening because of the high mass.

We have bombarded gold with slow neutrons from the 60″ cyclotron, and have collected enough of the transmutation product, mercury, to observe its spectrum. Since gold has only one isotope, 197, slow neutron capture gives rise to a single radioactive isotope, Au^{198}. This artificially radioactive product emits negative beta-rays with a half-life of 2.7 days and therefore turns into Hg^{198}, one of the stable isotopes of Hg. The experimental procedure is as follows:

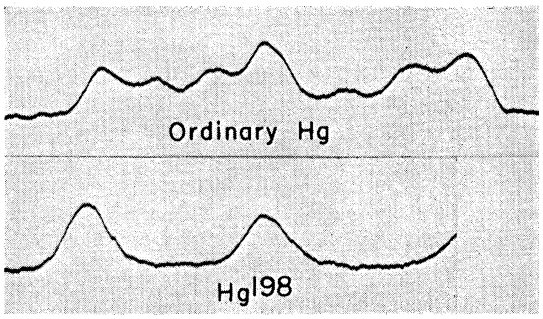

FIG. 1. Microphotometer traces for λ4047 from ordinary Hg and from Hg^{198}.

A cylinder of gold 15 cm long, 2.5 cm in diameter, and with a wall thickness of 0.2 mm is placed in a quartz tube of slightly larger diameter. To one end of this tube is fused a quartz capillary with an inside diameter of 2 mm. The whole system is evacuated and heated for 36 hours in a furnace almost to the melting point of gold. The gold is thus freed of any ordinary mercury contamination. Spectroscopically pure argon is then admitted to a pressure of 6 mm of Hg, and the quartz system is sealed off from the pumps. The gold cylinder in its quartz container is now placed in a paraffin-lined box near the target of the cyclotron, where it is bombarded with "stray" neutrons for about a month. At the end of this time the gold is again heated, while the end of the capillary tube is cooled in liquid air. After an hour of this treatment, a 3-cm length of the cooled capillary is sealed off. When the spectrum of the gas in this tube is excited by a 3-meter oscillator, the mercury lines are quite brilliant, but the argon spectrum is quenched. The mercury lines are visible after a neutron bombardment of a few hours, but they last for only a few seconds; under these conditions the Hg vapor is driven into the walls by the discharge. With a bombardment of a month, however, equilibrium between gas space and walls is apparently attained, so the spectrum is visible for some time. A microphotometer trace of a Fabry-Perot etalon spectrogram of the line λ4047 is shown in Fig. 1. The absence of the hyperfine components shows that the mercury is actually a transmutation product.

Since the Hg^{198} is a by-product of bombardments for biological purposes, no expenditure of "cyclotron time" is involved in its preparation. We will therefore be able to satisfy a reasonable demand for tubes filled with pure Hg^{198}, and we invite requests for such tubes. We gratefully acknowledge the support given to this work by the Research Corporation.

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