

allowing the liquid to leak out of a closed container through a superleak and measuring the concentration of the residual gas.

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¹L. W. Alvarez and R. Cornog, *Phys. Rev.* **56**, 613 (1939); **56**, 379 (1939).

²L. T. Aldrich and A. O. Nier, *Phys. Rev.* **70**, 983 (1946). At the time this work was done we did not feel that the accuracy of the measurements justified a correction for the difference in pumping speeds of He³ and He⁴ in the mass spectrometer pump lead. We now feel that the accuracy justifies this correction. Hence He³ abundances previously given should be multiplied by (4/3)³.

³E. Mathias, C. A. Crommelin, H. K. Onnes, and J. C. Swallow, *Leiden Comm.* 172b (1925).

Conductivity Pulses Induced in Diamond by Alpha-Particles

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THE modern theory of the solid state predicts that when alpha-particles bombard an insulator, the electrons freed by ionization will be raised to the conduction band. Under the influence of an applied electric field, these electrons, and the positive holes in the normally filled band, should move just as in the case of photo-conductivity. With a sufficiently high electric field across an insulator crystal which is relatively free of electron traps, it should be possible under favorable conditions to detect the movement of these charges and thus observe conductivity pulses.

With an amplifier and cathode-ray oscilloscope we have observed such pulses, produced by individual alpha-particles from radium, in diamond crystals at room temperature. The number of ions produced in diamond is of the same order as the number of ions produced by alpha-particles in an air ionization chamber. These conductivity pulses have been observed with two markedly different electrode arrangements on the diamond. One system consists of a pair of metal electrodes deposited by evaporation on the surface of the diamond, these electrodes being separated by a gap of 0.003 cm. Here the conductivity pulses consist of charges which travel across the top surface layers of the gap on the diamond. Good pulses were obtained with 5 volts applied across this gap. The second arrangement consists of evaporated electrodes on opposite sides of a diamond chip of about 0.5-mm thickness. Here the conductivity pulses consist of charges which travel from one surface toward the other surface of the diamond. Good pulses were obtained with 100 volts across such a diamond. In general, applied fields as low as 2000 volts per cm may be sufficient to approach saturation.

With each of the above electrode systems, pulses of comparable size are obtained with either direction of the applied field. When the applied field is reduced to zero, pulses are observed but for a short time only. These "space-charge" pulses are opposite in direction to those that occur when the voltage is applied, i.e., the diamond becomes polarized.

Our diamond specimens consist chiefly of "saw cuts," i.e., small chips sawed from a natural diamond in eliminat-

ing flaws, etc. Most of the diamonds which we have tested show this alpha-particle bombardment-induced conductivity. However, no conductivity pulses were observed in some diamonds even though saturation in photo-conductivity is approached at the applied fields used in the alpha-particle bombardment tests.

The electrodes apparently need to be in intimate contact with the diamond surface. Electrodes of gold, aluminum, or platinum formed by evaporation are satisfactory.

Van Heerden¹ has observed conductivity pulses induced by alpha-particle bombardment of silver chloride crystals at liquid nitrogen temperature, but he found none in the single diamond that he tried.

This phenomenon of bombardment-induced conductivity in diamond immediately suggests its use as a solid counter for nuclear physics experiments, particularly since it operates at room temperature. Its small size, high density, low operating voltage, and the possibility of rapid counting rate may give the diamond solid counter certain advantages over the conventional gas type counter.

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¹P. J. Van Heerden, Thesis (Utrecht, 1945).

Structure of the Quadrielectron*

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A PREVIOUS calculation led to the approximate value 0.11 ev for the binding energy of a system of two electrons and two positrons against dissociation into two free bielectrons.¹ The variational function leading to this result is the generalized "atomic" function

$$\psi_{\beta} = \frac{1}{2} \left\{ \exp -\frac{1}{2} [(1+\beta)(r_{1a}+r_{2b}) + (1-\beta)(r_{1b}+r_{2a})] \right. \\ \left. + \exp -\frac{1}{2} [(1-\beta)(r_{1a}+r_{2b}) + (1+\beta)(r_{1b}+r_{2a})] \right\}$$

where 1 and 2 refer to the electrons and *a* and *b* to the positrons.

This numerical result represented a considerable improvement as compared with the energy values resulting from earlier calculations, but it gave little information regarding the true value of the energy. For this reason an attempt has been made to determine the energy of the quadrielectron with greater accuracy.

The function, ψ_{β} , is related to the function used by S. C. Wang in the problem of the energy of the normal hydrogen molecule. A calculation has now been performed which is similar rather to Weinbaum's treatment of the hydrogen molecule by means of a linear combination of "atomic" and "ionic" functions,² which led to a considerable improvement in the energy value as compared to Wang's result.

For this purpose the following function has been used: $\Psi = \psi_{\beta} + c\psi_{\alpha}$, where the "ionic" function, ψ_{α} , is defined by

$$2\psi_{\alpha} = \exp -\frac{1}{2} [(1+\alpha)(r_{1a}+r_{2a}) + (1-\alpha)(r_{1b}+r_{2b})] \\ + \exp -\frac{1}{2} [(1-\alpha)(r_{1a}+r_{2a}) + (1+\alpha)(r_{1b}+r_{2b})] \\ + \exp -\frac{1}{2} [(1+\alpha)(r_{1a}+r_{1b}) + (1-\alpha)(r_{2a}+r_{2b})] \\ + \exp -\frac{1}{2} [(1-\alpha)(r_{1a}+r_{1b}) + (1+\alpha)(r_{2a}+r_{2b})].$$

Since Ψ does not contain the distances between particles

of the same kind, the method of calculating matrix elements developed in reference 1 is applicable. The calculations are tedious, however, and the resulting expression for the energy in terms of α , β , and c is rather complicated. Minimization of the energy leads to an optimum value for the binding energy of roughly 0.135 eV, when $\alpha = \beta = (0.5)^{1/2}$ and $c = 0.052$, approximately.

In previous calculations considerable improvement could be obtained by a slight improvement in the function. The fact that this is no longer true suggests that we might be near the convergence limit.

If we let ψ_β approximate the quadreelectron wave function, the mean distance between the various particles constituting this cluster is found to be roughly $\bar{r}_{12} = \bar{r}_{ab} = 4.5 \times 10^{-8}$ cm and $\bar{r}_{1a} = \bar{r}_{2b} = \bar{r}_{1b} = \bar{r}_{2a} = 3.0 \times 10^{-8}$ cm, that is, ψ_β gives reasonable relative values of the "repulsive" and the "attractive" distances. Furthermore, using the same function we find the value 1.16 for the ratio of the root mean square value of r_{12} to the mean value of this quantity. For the bielectron in the ground state, on the other hand, the corresponding ratio for the separation of the two particles has the value 1.15.

The values of the various mean distances reveal that the quadreelectron has a considerable size and, consequently, a large breakup probability when passing through matter even of small density.³

* The work here reported forms part of a dissertation presented for the degree of Doctor of Philosophy in Yale University.

¹ E. A. Hylleraas and A. Ore, Phys. Rev. **71**, 493 (1947).

² S. Weinbaum, J. Chem. Phys. **1**, 593 (1933).

³ For more details regarding the probability of breakup vs. annihilation of light polyelectrons see: J. A. Wheeler, Ann. New York Acad. Sci. **48**, 219 (1946).

The Hyperfine Structure of Atomic Hydrogen and Deuterium†

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THE hyperfine structure separation, ν_H and ν_D , of atomic hydrogen and deuterium were measured directly by means of the atomic beam magnetic resonance method.¹⁻³ For each atom two resonance lines were measured, each at the same value of the magnetic field, and the ν_H and ν_D were evaluated entirely from differences in the frequencies. Neither the value of the magnetic field nor the g values of the atomic and nuclear systems enter into the final result.

In H, where the value of the nuclear spin $I = 1/2$ and the atomic $J = 1/2$, the π -transitions $(1, 1) \leftrightarrow (0, 0)$ and $(1, 0) \leftrightarrow (1, -1)$ were measured at the same value of the magnet current. The difference between these two frequencies gives ν_H directly (see Eqs. 9-12 of reference 3). For D, where $I = 1$ and $J = 1/2$, the line $(3/2, 1/2) \leftrightarrow (1/2, -1/2)$, $(3/2, -1/2) \leftrightarrow (1/2, 1/2)$, an unresolved doublet, and the line $(3/2, 3/2) \leftrightarrow (1/2, 1/2)$ were measured in quite weak fields of the order of one gauss. The first line gives ν_D almost directly, and the difference in frequency of the two lines gives a small correction of less than 0.01 percent.

The measured values of ν_H and ν_D , in megacycles per second, are

$$\begin{aligned}\nu_H &= 1421.3 \pm 0.2 \\ \nu_D &= 327.37 \pm 0.03.\end{aligned}$$

The method is inherently capable of greater precision with the improvement of our frequency meter.

Since the theory of the H and D atoms is considered to be complete and exact, these values can be compared directly with calculations. The formula for the hyperfine structure separation of S states was given by Fermi⁴ and is

$$\nu = \frac{8\pi}{3h} \left(\frac{2I+1}{I} \right) \mu_N \mu_0 \psi^2(0). \quad (1)$$

The nuclear spin is denoted by I , μ_N is the magnetic moment of the nucleus in question, μ_0 is the Bohr magneton, and $\psi(0)$ is the value of the Schrodinger wave function evaluated at $r = 0$. $\psi^2(0)$ is proportional to $(1/a)^3$, the cube of the reciprocal of the radius of the first Bohr orbit. Since a is inversely proportional to the reduced mass, the appropriate value of the reduced mass, m_r , has to be inserted. If the values of the quantities in Eq. (1) are expressed in terms of the fundamental constants, Eq. (1) becomes

$$\nu = \frac{4}{3} \left(\frac{2I+1}{I} \right) \frac{\mu_N}{1836.6} \left(\frac{m_r}{m_0} \right)^3 \alpha^2 C R_\infty. \quad (2)$$

R_∞ is the Rydberg constant for infinite mass, α is the fine structure constant, and μ_N is the nuclear moment in terms of the nuclear magneton, $\mu_0/1836.6$. For μ_P and μ_D we have the accurate values of Millman and Kusch⁵

$$\begin{aligned}\mu_P &= 2.7896 \pm 0.0008 \\ \mu_D &= 0.85648 \pm 0.00037,\end{aligned}$$

for α^2 , R_∞ , and C we have the values given by Birge⁶

$$\begin{aligned}\alpha^2 &= (5.3256 \pm 0.0013) \times 10^{-5} \\ R_\infty &= 109737.303 \pm 0.017 \text{ cm}^{-1} \\ C &= (2.99776 \pm 0.00004) \times 10^{10} \text{ cm sec.}^{-1}\end{aligned}$$

With these values and the value of the ratio μ_P/μ_D given by Kellogg, Rabi, Ramsey, and Zacharias² and by Arnold and Roberts⁷ as 3.2571 ± 0.001 , we obtain the results given in Table I.

TABLE I. The hyperfine structure separation of H and D.

	Measured	Computed from Eq. (2)
ν_H	1421.3 ± 0.2 Mc	1416.90 ± 0.54 Mc
ν_D	327.37 ± 0.03 Mc	326.53 ± 0.16 Mc
ν_H/ν_D	4.3416 ± 0.0007	4.3393 ± 0.0014

There is clearly an important difference between the measured and calculated values of ν_H and ν_D of about 0.26 percent compared with the probable error of the calculated value of 0.05 percent. The difference is five times greater than the claimed probable error in the natural constants. Whether the failure of theory and experiment to agree is because of some unknown factor in the theory of the hydrogen atom or simply an error in the estimate of