

the expected background of 6. Even if the reported effect saturated at about the neutron emission rates reported by Grant and Cobble,<sup>1</sup> we should have observed 17 counts instead of 2.

We are very much indebted to Dr. C. J. Delbecq and Dr. B. Zadransky of this laboratory for considerable help in the experiment as well as to Mr. J. A. Beidelman and the staff of the Juggernaut Reactor. We are grateful to Professor Cobble for a helpful discussion.

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Atomic Energy Commission.

<sup>1</sup>T. J. Grant and J. W. Cobble, Phys. Rev. Letters **23**, 741 (1969).

<sup>2</sup>Grant and Cobble refer to an electron-neutron interaction potential of about  $-4000$  eV. This potential comes from the arbitrary assumption of a square well having a radius of  $2.8 \times 10^{-13}$  cm. A more precise statement of the result of the electron-neutron scattering experiment [V. E. Krohn and G. R. Ringo, Phys. Rev. **148**, 1303 (1966)] is that the volume integral of the interaction potential is  $3.47 \times 10^{-34}$  eV cm<sup>3</sup>. Thus, the electron-neutron interaction potential averaged over the volume of an atom would come to roughly  $10^{-10}$  eV.

## HYPERFINE STRUCTURE IN THE MOLECULAR ION $H_2^+$

K. B. Jefferts

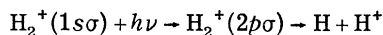
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

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I have observed 30 transitions between hyperfine levels of  $H_2^+$ , the simplest molecule. This is the first observation of the complete hyperfine structure for this system. The measured transition frequencies range from 3.989 to 1276.271 MHz, and fully define the hyperfine energy level schemes for the rotational states  $K=1$  and  $K=2$  and the vibrational states  $v=4-8$ .

Hyperfine structure in the simplest molecule  $H_2^+$  has been the subject of a considerable effort by radio astronomers, theorists, and experimentalists. To date,  $H_2^+$  has not been observed by the astronomers, no complete calculation has been done, and only meager experimental data have been available.

This rather unsatisfactory circumstance has been considerably improved by the observation of 30 transitions between hyperfine states of  $H_2^+$ , in rotational states  $K=1$  and  $K=2$ , and vibrational states  $v=4-8$ . The method utilizes  $H_2^+$  ions formed by electron impact from  $H_2$  at a pressure of the order of  $5 \times 10^{-9}$  Torr and contained in an rf quadrupole ion trap.<sup>1-3</sup> Electric dipole selection rules dominate the photodissociation reaction



induced by an intense light beam linearly polarized parallel to the static magnetic field. The  $H_2^+$  residue in the trap thus acquires an increasingly nonthermal distribution among hyperfine and Zeeman levels.

If the populations of two such levels are continuously equalized by driving the transition with an rf magnetic field at the resonance frequency, this fact manifests itself as an increase in the total photodissociation rate of the sample as mea-

sured by the ratio of the number of  $H^+$  photodissociation products to the remaining  $H_2^+$  at the end of the measurement cycle. A more complete

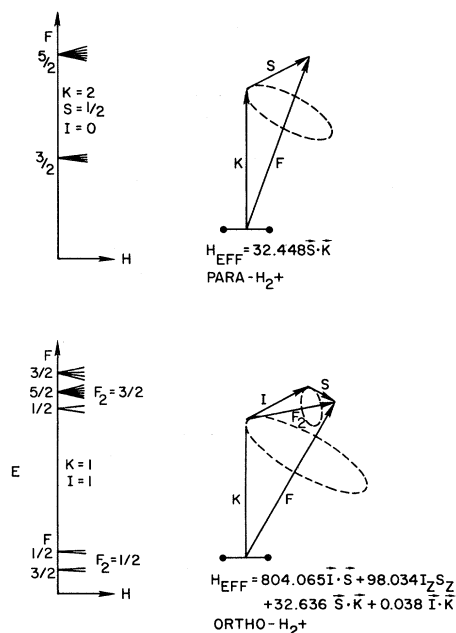


FIG. 1. Hyperfine energy levels, vector coupling schemes, and spin Hamiltonians for para- and ortho- $H_2^+$ . Hamiltonian coefficients in MHz, for vibrational state  $v=4$ .

Table I. Transition frequencies and Hamiltonian coefficients, in MHz, for vibrational states  $v=4$  through  $v=8$ , rotational states  $K=1$  and  $K=2$ .

$v$	FREQUENCIES BETWEEN STATES $F_2 F - F_2' F'$					$5/2 - 3/2$
	$3/2, 3/2 - 3/2, 5/2$	$3/2, 3/2 - 3/2, 1/2$	$1/2, 3/2 - 1/2, 1/2$	$3/2, 5/2 - 1/2, 3/2$	$3/2, 3/2 - 1/2, 3/2$	
4	5.721	74.027	15.371	1270.550	1276.271	81.121
5	5.258	68.933	14.381	1243.251	1248.509	75.601
6	4.817	63.989	13.413	1218.154	1222.971	70.231
7	4.395	59.164	12.461	1195.156	1199.551	64.977
8	3.989	54.425	11.517	1174.169	1178.159	59.804
	COEFFICIENTS					
	$b$	$c$	$d$	$f$		$d$
4	804.065	98.034	32.636	0.038		32.448
5	788.846	91.180	30.421	0.036		30.240
6	775.006	84.540	28.266	0.034		28.092
7	762.494	78.074	26.156	0.032		25.991
8	751.271	71.733	24.080	0.030		23.922
			K=1			K=2

description of the process may be found in Dehmelt and Jefferts,<sup>4</sup> Richardson, Jefferts, and Dehmelt,<sup>5</sup> and Jefferts.<sup>6</sup>

The hyperfine intervals were measured in low magnetic field, between 15 and 30 mOe, by superposing the various field-dependent transitions with the technique described in Ref. 6. This method leads to necessity for careful interpretation of line shapes and widths, but it is a practical requirement for adequate experimental signal-to-noise ratios. The observed widths vary from  $\pm 200$  to  $\pm 750$  Hz, corresponding to broadening induced by inhomogeneities in the static magnetic field of about  $\pm 2 \times 10^{-4}$  Oe.

In zero magnetic field, the hyperfine structure may be described by a spin Hamiltonian

$$H_{\text{eff}} = b\vec{I} \cdot \vec{S} + cI_z S_z + d\vec{S} \cdot \vec{K} + f\vec{I} \cdot \vec{K}.$$

Coefficients of the first three terms have been calculated by several authors.<sup>7-12</sup> Analysis of these data establishes the existence of the last term.

As a result of nuclear statistics, states of even rotational quantum number  $K$  necessarily have  $I=0$ . Thus the consequent Hamiltonian for para- $H_2^+$  is

$$H_{\text{eff}} = d\vec{S} \cdot \vec{K}.$$

Vector coupling schemes and energy-level diagrams are shown in Fig. 1. The coefficients in the Hamiltonians are appropriate for the vibrational state  $v=4$ .

The matrix elements of Ref. 2 have been corrected to include the nuclear spin-rotation term  $f\vec{I} \cdot \vec{K}$ , and the resulting energy formulas fitted to the observed spectra to determine the coupling coefficients. The measured transition frequencies and the resultant coefficients are shown in Table I. A uniform uncertainty of  $\pm 1.5$  kHz has

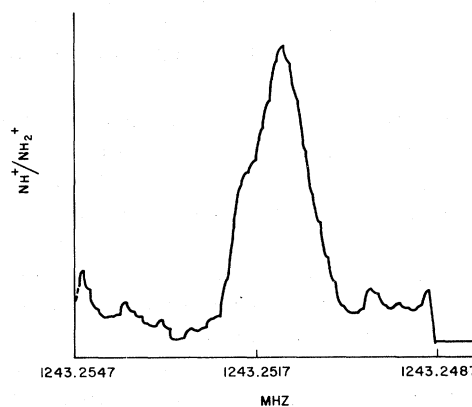


FIG. 2. Effective photodissociation rate as measured by the ratio  $N_{H^+}/N_{H_2^+}$  after 120 msec versus frequency of applied rf magnetic field.

been assigned because of the previously mentioned problems of line shape and experimental signal-to-noise ratios. A typical measurement is illustrated in Fig. 2.

The observed frequencies for the transition ( $F_2$ ,  $F_1$ ) =  $\frac{3}{2}$ ,  $\frac{5}{2}$  -  $\frac{1}{2}$ ,  $\frac{3}{2}$  have been extrapolated to the zeroth vibrational state, yielding a frequency 1404.3 MHz.<sup>13</sup> This is expected to be the most intense transition of astronomical interest.<sup>14</sup>

It is a pleasure to acknowledge the many contributions of Professor H. G. Dehmelt, who originally suggested the problem to the author; of A. J. Massick, who constructed much of the apparatus; and of J. I. Gersten, whose interest and aid have been of much value.

<sup>1</sup>W. Paul, O. Osberg, and E. Fischer, *Forschungsber. Wirtsch.-Verkehrsministeriums Nordrhein-Westfalen* No. 415 (1968).

<sup>2</sup>R. F. Wuerker, H. Shelton, and R. V. Langmuir, *J. Appl. Phys.* **30**, 342 (1958).

<sup>3</sup>H. G. Dehmelt, *Advances in Atomic and Molecular Physics* (Academic Press, Inc., New York, 1967), Vol. 3.

<sup>4</sup>H. G. Dehmelt and K. B. Jefferts, *Phys. Rev.* **125**, 1318 (1962).

<sup>5</sup>C. B. Richardson, K. B. Jefferts, and H. G. Dehmelt, *Phys. Rev.* **165**, 80 (1968).

<sup>6</sup>K. B. Jefferts, *Phys. Rev. Letters* **20**, 39 (1968).

<sup>7</sup>M. J. Stephen and J. P. Aufray, *J. Chem. Phys.* **31**, 1329 (1959).

<sup>8</sup>A. Dalgarno, T. N. L. Patterson, and W. B. Somerville, *Proc. Roy. Soc. (London)*, Ser. A **259**, 100 (1960).

<sup>9</sup>B. F. Burke, *Astrophys. J.* **132**, 514 (1960).

<sup>10</sup>M. Mizushima, *Astrophys. J.* **132**, 493 (1960).

<sup>11</sup>W. B. Somerville, *Monthly Notices Roy. Astron. Soc.* **139**, 163 (1968).

<sup>12</sup>S. K. Luke, *Astrophys. J.* **156**, 761 (1969). It is to be noted that the tentative assignment of vibrational quantum numbers made in Ref. 6 has been confirmed in the present work, thereby refuting the speculations contained in the above regarding second-order contributions to the electron spin-rotation interaction, and the frequencies of astronomical interest. In particular, the present work confirms the frequency prediction of A. A. Penzias *et al.*, *Astrophys. J.* **154**, 389 (1968).

<sup>13</sup>The extrapolation was performed by fitting the observed frequencies to a fourth-order polynomial in  $v$ , the vibrational quantum number. One additional transition in the state  $v=9$  at 1155.1195 MHz was subsequently identified, which defines the coefficient of the fifth-order term to be zero within the accuracy of the present experiment. It is expected the extrapolation produces an error of the  $v=0$  frequency less than 0.1 MHz.

<sup>14</sup>Penzias *et al.*, Ref. 12. Another search for the 1404.3-MHz transition has recently been made by the same group, and will be reported elsewhere.

## STARK SHIFTS WITHIN THE $(1s2s)^3S_1$ STATE OF He†

A. T. Ramsey and R. Petraso

Department of Physics, Brandeis University, Waltham, Massachusetts 02154

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We have measured the relative Stark shift between the  $m_J = \pm 1$  and the  $m_J = 0$  Zeeman sublevels of the  $2^3S_1$  metastable state in helium. This shift should be zero in the  $L-S$  coupling limit. The shift is  $(1.27 \pm .04) \times 10^{-6}$  Hz/(V/cm)<sup>2</sup>, and decreases the normal magnetic field splitting between the  $m_J = +1$  and the  $m_J = 0$  sublevels.

Recently there has been considerable interest in the study of Stark shifts of atomic levels. Two main approaches have been used. One is a study of the shifts between the hyperfine levels of a given  $J$  state or the Zeeman sublevels of a single level, usually in the presence of both electric and magnetic fields.<sup>1</sup> Also, shifts of the optical transitions have been studied by the use of beam-absorption spectroscopic methods.<sup>2</sup> The reasons for this revival of interest are several; among them are improved methods for the measurement of very small shifts in resonance lines,<sup>3</sup> improved techniques for handling the calculations

involved in understanding the data,<sup>4</sup> and, in the case of the beam absorption technique, improved methods for producing very high electric fields.

We wish to report here the results of a measurement of the relative shift between the  $m_J = \pm 1$  and the  $m_J = 0$  sublevels of the  $(1s2s)^3S_1$  state of He caused by a uniform electric field.<sup>5</sup> The measurement was made in the presence of a magnetic field parallel to the electric field.

A schematic representation of the apparatus is given in Fig. 1. The source was a 0.008-in.-wide slit. The beam was excited to the metastable  $^3S$  state by electron bombardment in a gun