produced just within the diamagnetic plasma itself.[7] Since it has been estimated[8] that the inner edge of the neutral sheet is at 8 earth radii, we take

$$B_0 = M/2r_N^{\,3} = 30\,\gamma.$$

The resulting field in the midnight meridian is plotted in Fig. 2. It is interesting to note that the field line which reaches out to the inner edge of the neutral sheet at 8 earth radii is at a latitude of 67° at the surface of the earth. This boundary thus forms a natural path for the high-energy electrons observed in the tail of the magnetosphere to enter the auroral zone.

One final point should be made. In order to simplify the discussion, considerations of corotation of the magnetosphere were left out. However, injection of solar-wind plasma will still take place, with the path of such a particle in the tail being the vector sum of the drift path and the corotating path. Therefore, solar plasma will still enter the tail and dominate the magnetic field beyond about 8 earth radii.

[1]N. F. Ness, C. S. Scearce, and J. B. Seek, Proc. Intern. Space Sci. Symp., 5th, Florence, 1964 (to be published).

[2]S. F. Singer, Trans. Am. Geophys. Union 38, 175 (1957).

[3]A. J. Dessler and E. N. Parker, J. Geophys. Res. 64, 2239 (1959).

[4]H. A. Bridge, A. Egidi, A. Lezarus, E. Lyon, and L. Jacobson, Proc. Intern. Space Sci., Symp., 5th, Florence, 1964 (to be published).

[5]E. N. Parker, Phys. Fluids 1, 171 (1958).

[6]R. C. Wentworth and L. R. Tepley, J. Geophys. Res. 67, 3335 (1962).

[7]J. R. Apel, S. F. Singer, and R. C. Wentworth, Advances in Geophysics IX, edited by H. F. Landsberg (Academic Press, Inc., New York, 1962).

[8]N. F. Ness, private communication.

RESONANCE PHENOMENA IN THE SCATTERING OF ELECTRONS BY H_2 AND D_2†

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A modified Ramsauer[1] technique has been used to observe electron-molecule resonance cross-section structures in H_2 and D_2. Energy values of the resonance minima in electron scattering from H_2 have been previously given.[2] Values of the energy and changes in cross section at the resonances are reported in this paper for both H_2 and D_2.

The apparatus used for the present measurements is described in detail elsewhere.[3] For the present work, the electrons were momentum selected by the 180° magnetic momentum selector and then collected. The selection region was also used as the scattering region. A constant pressure of either H_2 or D_2 of between 0.015 and 0.030 Torr was maintained in the whole chamber while the electron energy was varied. The energy was determined by making retarding-potential measurements on the transmitted electron beam.[4] The electron-beam width at half-height during these measurements was about 0.1 eV.[3] The transmitted beam current when plotted versus electron energy over a small range of energy was found to change because there is a gradual change in cross section, and also fewer electrons get through the selection system as the energy is decreased. In order to greatly increase the sensitivity for detection of small changes in the cross section with energy in the presence of a large background cross section, a diode function generator was used to buck out this changing background. The resulting signal could then be greatly amplified. Using this technique, the electron energy was varied between about 1.5 and 15.6 eV in overlapping steps of between about 0.5 to 1.5 eV.

Figure 1 shows a plot of the resonance cross-section decrease in H_2 versus electron energies between about 10.7 and 12.9 eV. Eight minima are observed. Figure 2 shows a plot similar to Fig. 1, but for D_2 rather than H_2. Here the resonances are closer together, and nine minima are observed. The plots actually represent average values obtained from many runs. Some of the data were obtained by bucking out the changing background with a signal proportional to the accelerating volt-

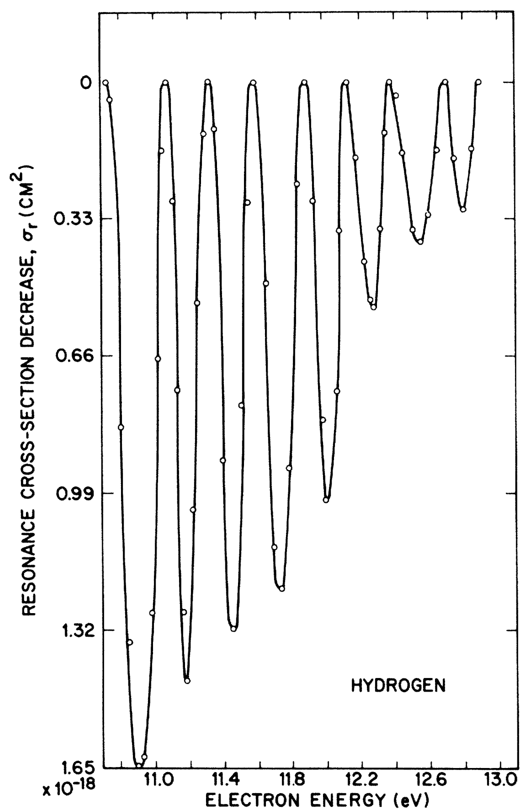

FIG. 1. Resonance cross section (decrease) in hydrogen versus electron energy using Eq. (2).

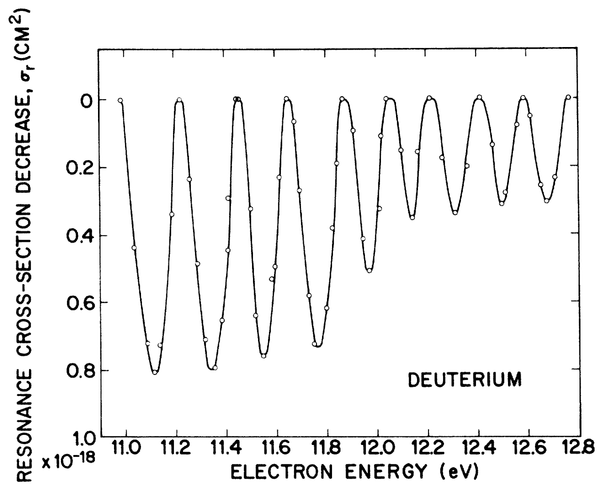

FIG. 2. Resonance cross section (decrease) in deuterium versus electron energy using Eq. (2).

age. This clearly demonstrated that the resonances were decreases in cross section. The absolute magnitude of the decreases in cross section certainly depend on the instrumental resolution.[3] However, in the present work the resonance half-width is much broader than the electron beam half-width and so should not affect the magnitude of the cross-section decrease to any great extent. There was also structure observed at the lowest electron energies studied but the signal-to-noise ratio is too poor for quantitative measurements at this time.

A comparison between Fig. 1 and Fig. 2 shows the lower energy resonance cross section at the minima in H_2 to be about twice as large as those in D_2, while those for higher electron energies are about the same.

The transmitted current $I(E)$, which depends on the electron energy E, may be written

$$I(E) = I_0(E) \exp\{-[\sigma_t(E) + \sigma_r(E)]nx\}, \qquad (1)$$

where $I_0(E)$ is the initial current leaving the cathode, $\sigma_t(E)$ is the background scattering cross section, $\sigma_r(E)$ is the change in cross section at resonance which is small compared to $\sigma_t(E)$, n is the gas density, and x is the path length of the electron beam through the gas. If the gross current variation is subtracted from Eq. (1), the change in current due to $\sigma_r(E)$ may be written

$$\delta I(E) = \{I_0(E) \exp[-\sigma_t(E)nx]\}\{-\sigma_r(E)nx\}, \qquad (2)$$

where it has been assumed that $\sigma_r(E)nx \ll 1$. If the first factor of Eq. (2) is approximated by the measured current (which should be a very good approximation in the present case), Eq. (2) may be used to obtain a good approximation for $\sigma_r(E)$. Using Eq. (2) as outlined, the cross-section scale on the figures was obtained. The positions of the cross-section minima are reproducible to about ±0.03 eV. The absolute energy scale is probably good to ±0.1 eV. The cross-section changes at resonance are reproducible to about 1×10^{-19} cm^2.

There are a number of electronic levels in the vicinity of the observed structures.[5] For hydrogen, the lowest observed level by electron impact seems to be the $v=2$ vibrational state of the $^1\Sigma_u{}^+$ electronic level at 11.5 eV.[6] The next level observed by electron impact seems to be at 11.8 eV, and is designated by $v=0$, $^3\Sigma_g{}^+$ by Massey and Burhop.[6] The presently observed cross-section minima spacings

Table I. Observed position of resonances in H_2, and a comparison between the observed resonance spacings and some vibrational spacings of H_2.

Observed resonance: Cross section minima energy (eV)	Spacing (eV)	Vibrational spacings in H_2: $^1\Sigma_u^+$ B (eV)	$^3\Pi_u$ c (eV)	$^1\Pi_u$ C (eV)
10.93				
	0.29	0.164	0.290	0.286
11.22				
	0.26	0.159	0.275	0.270
11.48				
	0.28	0.155	0.260	0.253
11.76				
	0.28	0.152	0.245	0.236
12.04				
	0.27	0.148	0.229	0.220
12.31				
	0.27	0.146	0.214	0.203
12.58				
	0.23		0.199	0.187
12.81				

Table II. Observed position of resonances in D_2, and a comparison between the observed resonance spacings and the vibrational spacings of $^3\Sigma_g^+$ and $^1\Pi_u$ of D_2.

Observed resonance: Cross section minima energy (eV)	Spacing (eV)	Vibrational spacing: $^3\Sigma_g^+$ a (eV)	$^1\Pi_u$ C (eV)
11.14			
	0.23	0.225	0.206
11.37			
	0.21	0.216	0.198
11.58			
	0.22	0.208	0.191
11.80			
	0.20	0.200	0.184
12.00			
	0.17	0.193	0.180
12.17			
	0.17	0.185	0.175
12.34			
	0.19	0.177	0.171
12.53			
	0.18	0.171	0.170
12.71			

in H_2 are compared with some vibrational spacings for H_2,[5] in Table I.[7] The spacing between the minima of the observed structure fits best to the spacings of the vibrational states of either the $^3\Sigma_g^+$ or the $^3\Pi_u$ levels. However, it would almost fit within the experimental error with the spacings associated with either the $^1\Pi_u$ or $^1\Sigma_g^+$ levels. If this series of resonances is to be associated with the $^1\Sigma_u^+$ levels, it would mean either that only every other level is observed or that there is a complicated interference effect due to phase differences between alternate resonances. The spacings of this series of resonances are probably too large to be associated with the spacings of the ground state of H_2^+.[2] The higher energy resonances seem to be somewhat broader than the lower energy ones. The $v=0$, $^3\Pi_u$ is 0.036 eV lower than the $v=0$, $^3\Sigma_g^+$ level.[5] However, the vibrational levels associated with the $^3\Pi_u$ get closer together faster than the vibrational levels associated with the $^3\Sigma_g^+$. This might account for the broadening observed as well as the failure of the resonance spacings to decrease as fast as the vibrational spacings with electron energy.[8]

The observed spacings of the cross-section minima in D_2 are compared with some vibrational spacings[5] in D_2 in Table II.[7] As is the case in H_2, the spacings of the observed minima fit either the $^3\Sigma_g^+$ or the $^1\Pi_u$ vibrational spacings.

The energy difference of 0.21 eV between the first minimum in H_2 and that in D_2 is at first surprising. The electronic energy difference is at most about 0.06 eV for the neutral molecules.[5] Our data showed some indication of another cross-section minimum at about 0.2 eV below the lowest energy one in Fig. 2. However, at this time our signal-to-noise ratio can only place an upper limit of 1×10^{-19} cm^2 on its possible existence. We are presently investigating this point.

The rather large difference between the energy scale as given for the present H_2 results when compared to the energy scale as given by Kuyatt, Mielczarek, and Simpson[2] may be explained on the basis of their choice of the appearance potential of H_2^+.[9] If 15.4 eV is used, the resonance energies of Kuyatt, Mielczarek, and Simpson[2] are in reasonable agreement with those of the present work in H_2 with the experimental errors involved.

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[1]C. Ramsauer, Ann. Phys. 66, 546 (1925).

[2]C. E. Kuyatt, S. R. Mielczarek, and J. Arol Simpson, Phys. Rev. Letters 12, 293 (1964).

[3]D. E. Golden and H. W. Bandel, Phys. Rev. 138, A14 (1965).

[4]An energy check of the position of the elastic resonance in He showed the minimum cross section to be at 19.285 eV.

[5]G. Herzberg, Molecular Spectra and Molecular Structure. Spectra of Diatomic Molecules (D. Van Nostrand Company, New York, 1950), 2nd edition.

[6]H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena (Clarendon Press, Oxford, 1952).

[7]Energy values in the tables have been corrected for a 0.03-V contact potential in the electrometer.

[8]This is in disagreement with the spacings found in reference 2.

[9]P. E. Golden and D. Rapp, Lockheed Missiles and Space Company Technical Report No. 6-74-64-12 (unpublished); D. D. Briglia and D. Rapp, Phys. Rev. Letters 14, 245 (1965).

LASER DOUBLE-QUANTUM PHOTODETACHMENT OF I^- †

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Since the advent of lasers, many types of multiple-photon absorption processes have been investigated,[1-4] principally between bound states in solids. We report here the results of an experimental study of two-quantum induced photodetachment of electrons from a beam of negative ions of atomic iodine (I^-) in high vacuum. Because of the simplicity of the energy level spectrum of I^- (only one bound state, at −3.076 eV), it might be expected that rather detailed comparison of experimental results with theory should be feasible.

For completeness, we summarize here briefly the theoretical situation. The transition probability per second for a two-photon absorption process is given by

$$W_2 = \frac{2\pi}{\hbar}\left|\sum_n \frac{\langle i|H|n\rangle\langle n|H|f\rangle}{(E_i + 2h\nu)-(E_n + h\nu)}\right|^2 \rho(E), \qquad (1)$$

where H is the interaction Hamiltonian, $\rho(E)$ is the density of final states, and E_i and E_n are the energies of $|i\rangle$ and $|n\rangle$. Geltman[5] has evaluated Eq. (1) for transitions from the single bound state of (atomic) halogen negative ions to the continuum, using the plane-wave approximation for the free-electron states. A particularly simple result is obtained in this approximation, since the only intermediate state $|n\rangle$ which contributes to the sum in Eq. (1) is the state $|n\rangle = |f\rangle$. This makes W_2 proportional to the known single-quantum photodetachment cross section σ at twice the laser frequency. Using the measured[6] value of σ, Geltman's result may be written

$$W_2 = \delta F^2 \text{ with } \delta = 5\times 10^{-51} \text{ cm}^4 \text{ sec},$$

where the photon flux F is in photons $\text{cm}^{-2}\,\text{sec}^{-1}$. For our typical $\frac{1}{3}$-μA beam of 500-eV ions focused through an area 0.1 cm^2 and crossed by a 1-J, 20-MW Q-switched ruby laser focused through an area 10^{-2} cm^{-2}, this value of δ leads to an expectation of about 30 double-quantum photodetached electrons per laser pulse.

We describe here a measurement of the value of δ at $h\nu = 1.785$ eV, using the apparatus schematically depicted in Fig. 1.[7] Iodine negative ions are generated in a hot cathode arc discharge operated in ammonia and I_2 vapor at 30 μ pressure. Negative ions are extracted, accelerated, mass-analyzed, slowed, and then focused by an "einzel" lens into an area of about 9 mm^2 where they are crossed with the laser beam. The detached electrons are focused onto the first dynode of an electron multiplier. Some difficulty was experienced with spurious electrons removed by the laser, perhaps thermally, from the silvered mirror which redirects the laser beam to the laser monitor external to the vacuum system. Biasing the interaction region a few volts negative effectively reduced collection of these spurious charges. The residual signal may just be seen in Fig. 2(b), and was never more than a few electrons. To

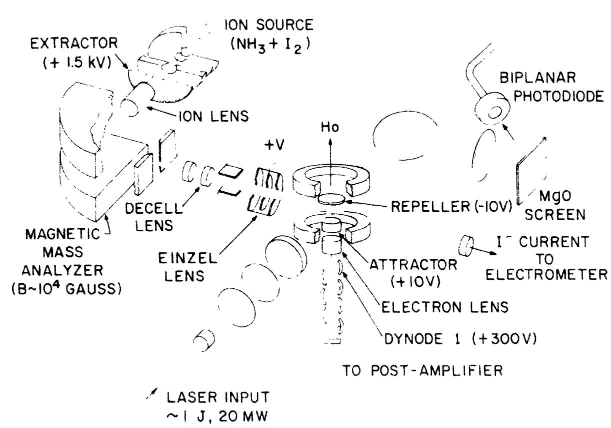

Fig. 1. Schematic diagram of the apparatus. For clarity the movable phosphor is not illustrated. The $\frac{1}{2}$-in. diameter by 4-in. long optically excellent ruby was run close to threshold, being Q switched by a rotating plane mirror.