Double-Electron Capture by Protons in H_2 Gas*

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The cross section for capture of two electrons by protons in single collisions with H_2 molecules has been redetermined in order to obtain an independent check on the several previous measurements of Fogel and co-workers. The apparatus utilizes a gas proportional counter as a detector of both the fast H^- ions resulting from double-electron capture and the fast H atoms resulting from single-electron capture. The known cross section for the single-electron capture process provided a firm basis for calibration of the apparatus. It was found that the H^- production cross section reached a maximum of 1×10^{-17} cm^2/gas molecule at an incident proton energy of 20 keV in agreement with the latest Fogel results; however, the shape of the presently measured cross-section curve differs greatly on either side of the maximum from the Fogel curve. This discrepancy appears to be far outside the limits of experimental error.

DOUBLE-electron capture by protons in H_2 gas, symbolically represented

$$H^+ + H_2 \rightarrow H^- + 2H^+, \quad (1)$$

has been studied by Fogel and co-workers on several occasions.[1–4] The experimental technique consisted of passing a monoenergetic beam of fast protons through a differentially pumped H_2 target chamber and observing the emergent fast H^- ions. The more recent results[4] show a sharply peaked cross section versus energy curve with a maximum cross section of $\sim1.0\times10^{-17}$ cm^2 occurring at a proton energy of 20 keV. The process is of special interest among experimentally studied atomic-charge transfer processes in that only two electrons are present in the colliding system and both are transferred from bound states on the target particle to bound states on the incident particle: There is no possibility of free-electron production. Furthermore, the colliding particles are in their ground states prior to the collision and any electronic excitation existing among the product particles must reside in the bound electrons of H^-. Rough theoretical arguments suggest that H^- has no bound excited states. Because of these circumstances, reaction (1) is an exceptionally well-defined process worthy of very careful study.

We have attempted to verify the results of Fogel *et al.* using an apparatus employed in an earlier study[5] of charge transfer and dissociation of H^+, H_2^+ and H_3^+ ions. A diagram of the apparatus is given in Ref. 5. A beam of monoenergetic protons was prepared as before and directed through the collision chamber T_2 of Ref. 5. Particles emergent from the collision chamber were mechanically scanned by a gas proportional counter having a narrow entrance slit. The collision products H and H^- were counted individually with a multichannel pulse-height analyzer. The large exit aperture of the collision chamber made possible the collection of all secondary reaction products produced up to 2.6° from the primary beam. The size of this aperture in comparison with the collision chamber length made it difficult to calculate the pressure profile in the collision chamber, consequently, the apparatus was calibrated as in our earlier measurements[5] using the well-known single electron-capture process as a standard. $\sigma_{1,0}$ the single electron-capture cross section, and $\sigma_{1,-1}$, the double-capture cross section, were measured alternately at each of several energies in the range 6 to 50 keV. To eliminate background effects, a particle count versus collision-chamber pressure curve was taken for every individual cross section measurement. The slope of the curve was

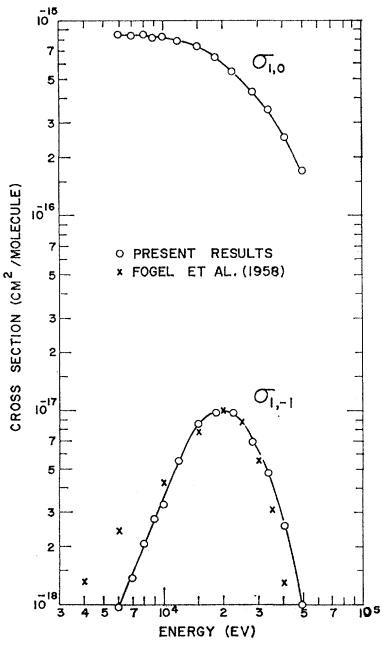

FIG. 1. Cross sections for single- and double-electron capture by protons colliding with hydrogen molecules. $\sigma_{1,0}$—single-electron-capture cross section. $\sigma_{1,-1}$—double-electron-capture cross section. The present results are normalized to an absolute scale by setting $\sigma_{1,0}$ equal to 8.2×10^{-16} cm^2 at 10 keV. The data of Fogel are taken from Ref. 4.

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[1] Ia. M. Fogel, L. I. Krupnik, and B. G. Safronov, Zh. Eksperim. i Teor. Fiz. **28**, 589 (1955)[translation: Soviet Phys.—JETP **1**, 415 (1955)].

[2] Ia. M. Fogel and L. I. Krupnik, Zh. Eksperim. i Teor. Fiz. **29**, 209 (1955) [translation: Soviet Phys.—JETP **2**, 252 (1956)].

[3] Ia. M. Fogel and R. V. Mitin, Zh. Eksperim. i Teor. Fiz. **30**, 450 (1956) [translation: Soviet Phys.—JETP **3**, 334 (1956)].

[4] Ia. M. Fogel, R. V. Mitin, V. F. Kozlov, and N. D. Romashko, Zh. Eksperim. i Teor. Fiz. **35**, 565 (1958) [translation: Soviet Phys.—JETP **8**, 390 (1959)].

[5] G. W. McClure, Phys. Rev. **130**, 1852 (1963).

used as the measure of relative cross section. The collision chamber pressure was maintained below 10^{-4} Torr to insure that multiple collisions were not occurring and to insure that the primary proton beam was not significantly attenuated. The primary proton-beam current was monitored by a Faraday cup beyond the collision chamber. Variations in this current during the beam scans were automatically compensated for by a newly developed servo system, which drove the proportional counter scanning mechanism at a speed proportional to the beam current arriving in the Faraday cup. The addition of this servo system was the only change made in the apparatus described in Ref. 5.

Careful tests were performed to ascertain that the negative ions emergent from the collision chamber were not produced by single-electron capture on a small fraction of H atoms present in the beam entering the collision chamber.

The negative ions were found to emerge from the collision chamber in a beam less than $\frac{1}{2}°$ wide, indicating that the collision chamber exit solid angle and the length of the detector slit were both adequate to transmit all of the fast H^- ions produced. The negative ions were deflected by the electrostatic deflection plates through an angle equal and opposite to the angle of positive ion deflection, and the pulse-height distribution produced by the negative ions was exactly the same as that produced by the primary protons.

The experimental results are shown in Fig. 1. The collision-chamber calibration factor was chosen so as to normalize the $\sigma_{1,0}$ curve to the value 8.2×10^{-16} cm^2 at 10 keV. With the same factor applied to all cross section values, the $\sigma_{1,0}$ curve was found to fit within a few percent the mean of several sets of absolute data taken from a recent review article.[6] The $\sigma_{1,-1}$ curve agrees well with the latest Fogel results[4] near the maximum, but departs seriously from these results on either side of the maximum. The discrepancy is far outside an estimated $\pm10\%$ uncertainty of the present data.

[6] S. K. Allison and M. Garcia Munoz, in *Atomic and Molecular Processes*, edited by D. R. Bates (Academic Press Inc., New York, 1962), p. 751.

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Quadrupole Antishielding Factors of Ions*

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Values of the quadrupole antishielding factor γ_∞ have been calculated for the F^-, Br^-, Rb^+, Pr^{3+}, and Tm^{3+} ions, using the method of direct solution of the inhomogeneous Schroedinger equation for the perturbed wave functions.

A SUMMARY of calculated values of the quadrupole antishielding factor[1-3] γ_∞ has been given in a recent paper.[4] The purpose of the present note is to give the results of additional calculations of γ_∞ for the following ions: F^-, Br^-, Rb^+, Pr^{3+}, and Tm^{3+}. The method of calculation is the same as in our earlier work.[3,4] For F^-, Br^-, and Rb^+, Hartree-Fock wave functions were used. For the two rare-earth ions, Pr^{3+} and Tm^{3+}, only Hartree functions are available for the calculations.

The method of calculation will be briefly outlined. The contribution $\gamma_\infty(nl\rightarrow l)$ to γ_∞ due to a given radial mode of excitation $(nl\rightarrow l)$ is given by

$$\gamma_\infty(nl\rightarrow l)=C_{ll}^{(2)}\int_0^\infty u_0'u_1'r^2dr, \tag{1}$$

where u_0' is r times the unperturbed radial wave function, normalized to 1; u_1' is r times the perturbation of the wave function, and is determined by the equation

$$\left[-\frac{d^2}{dr^2}+\frac{l(l+1)}{r^2}+V_0-E_0\right]u_1'=u_0'\left(\frac{1}{r^3}-\left\langle\frac{1}{r^3}\right\rangle_{nl}\right), \tag{2}$$

together with the orthogonality condition

$$\int_0^\infty u_0'u_1'dr=0. \tag{3}$$

In Eq. (1), the coefficient $C_{ll}^{(2)}$ represents the effect of the integration over the angular variables and the summation over the magnetic substates. We have $C_{11}^{(2)}=48/25$ for $np\rightarrow p$, and $C_{22}^{(2)}=16/7$ for $nd\rightarrow d$, for completed p and d shells, respectively. In Eq. (2), $\langle1/r^3\rangle_{nl}$ is the average value of $1/r^3$ for the wave function u_0'. In solving Eq. (2), the expression V_0-E_0 on the left hand side is directly obtained from the unperturbed function u_0', as follows

$$V_0-E_0=\frac{1}{u_0'}\frac{d^2u_0'}{dr^2}-\frac{l(l+1)}{r^2}. \tag{4}$$

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] R. M. Sternheimer, Phys. Rev. **84**, 244 (1951).
[2] H. M. Foley, R. M. Sternheimer, and D. Tycko, Phys. Rev. **93**, 734 (1954).
[3] R. M. Sternheimer and H. M. Foley, Phys. Rev. **102**, 731 (1956).
[4] R. M. Sternheimer, Phys. Rev. **130**, 1423 (1963).