DETACHMENT OF ELECTRONS FROM H^- BY ELECTRON IMPACT*

G. Tisone and L. M. Branscomb
Joint Institute for Laboratory Astrophysics,† Boulder, Colorado
(Received 27 June 1966)

The negative ion of atomic hydrogen, H^-, is the predominant source of opacity in most stellar photospheres. Among the collision processes responsible for its destruction, and hence contributing to the approach to local thermodynamic equilibrium in its abundance, is ionization by electron impact:

$$e + H^- \rightarrow H + 2e. \tag{1}$$

No experimental determinations of the cross section for this process have been reported. Theoretical predictions[1-4] have given values which differ both in energy dependence and maximum cross section by several orders of magnitude. This Letter reports an experimental determination[5] of the absolute cross section at 100-eV electron energy, and the energy dependence from 30 to 500 eV.

A mass-analyzed beam of 2.5-keV H^- ions (about 4×10^{-8} A) is bombarded by an electron beam (about 30 μA) in a region of high vacuum (about 5×10^{-8} Torr). Ions surviving the collision region are swept, electrostatically, into a Faraday cup, while neutral hydrogen atoms formed by process (1) fall on a suitable neutral detector. The flux of 2.5-keV neutral hydrogen atoms which constitutes the signal is accompanied by other atoms resulting from the stripping of H^- ions on slit edges and the background gas. Ultraviolet photons which result from the interaction of the electron beam with metal surfaces and gas in the interaction volume are also seen by the detector. To discriminate against these sources of noise in the neutral detector, both the ion beam and the electron beam are symmetrically chopped (at 50 cps and 20 kc/sec, respectively). The neutral-atom signal is measured by using the integrated output of two synchronous detectors in series, each synchronized at the appropriate chopping frequency, thus preserving the signal contained in both sidebands. That component of the neutral-particle flux which is detected by the double demodulation is

$$N_0(t) = \left(\frac{4}{\pi}\right)^2 \frac{\bar{I}}{e}\frac{\bar{J}}{e} F \frac{(v^2+V^2)^{1/2}}{vV}\sigma \sin\omega_i t \sin\omega_j t, \tag{2}$$

where σ is the cross section for Reaction (1), e is the electronic charge, v and V are the speeds of the electron and ions, respectively, and $\bar{I}$ and $\bar{J}$ are the average ion and electron currents. The form factor F which describes the spatial distributions of the electron and ion beams in the region of interaction is given by

$$F = \frac{\int i(z)j(z)dz}{\int i(z)dz \int j(z)dz}, \tag{3}$$

where

$$i(z) = \partial I/\partial z, \quad j(z) = \partial J/\partial z.$$

This form factor is the reciprocal of the effective height of the ion beam and is measured by means of a movable scanning plate, which intersects both electron and H^- beams and which provides an integral measure of their spatial distributions. Values of F^{-1} in the data reported varied from 0.252 to 0.200 cm. The dc-output signal from the synchronous detectors is related to the time-varying neutral flux, $N_0(t)$, through calibration of the gains of the amplifiers and detectors, which is straightforward, and through calibration of the neutral detector, for which a special set of experiments is required.

The neutral-atom detector utilizes secondary emission and subsequent phosphor excitation. The atoms strike a Cu-Be plate inclined at 60° to the beam and biased to a potential of 10 kV. Secondary electrons (2.56 per atom for 2.5-keV H atoms) excited a plastic scintillator near ground potential. The photons from the scintillator were then detected by a photomultiplier tube. The calibration of this detector system was accomplished in several steps. First the secondary-emission coefficient (γ_{H^-}) for the Cu-Be plate was related to a known flux of H^- ions (with the plate grounded so that ions struck it with 2.5 keV of kinetic energy). In a separate photodetachment experiment, neutral H atoms were produced through the process

$$h\nu + H^- \rightarrow H + e, \tag{4}$$

and the secondary emission coefficient for neutral hydrogen atoms (γ_{H^0}) was shown to be equal to that for negative ions of the same energy.

Table I. Measured cross sections for detachment of an electron from H^- by electron impact.

Energy (eV)	Cross section (πa_0^2)	50% confidence limits in cross section relative to 100 eV (%)
30	42.2	−17, 10
50	34.6	−17, 10
100	24.5	•••
200	16.4	±16
300	12.9	±16
400	10.1	±19
500	9.8	±19

It remained to prove that all the observed signals were due to process (1) and not to spurious sources that are well known to plague crossed-charged-beam experiments. Most serious is the space-charge modulation of the negative-ion trajectories with subsequent conversion of the ions to neutrals through stripping on slit edges or residual gas. In addition to requiring the signal to be linearly proportional to ion current and electron current, we required the H^- and D^- cross sections for fixed electron and ion energies to be the same. This test discriminates between true signal and space-charge-modulated stripped neutrals.

Results are given in Table I. Figure 1 shows that the relative cross section exhibits accurately the general behavior

$$\sigma(E)=\frac{A}{E}\log\frac{E}{B}, \tag{5}$$

where A and B are constants and E is the incident electron energy, as expected if the Bethe approximation is applicable. In Fig. 2 we see that McDowell and Williamson's calculation in this approximation is approximately correct.

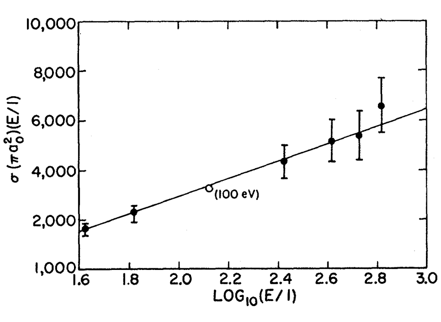

FIG. 1. The product $(E/I)\sigma$ as a function of $\log(E/I)$, where $I=0.75$ eV.

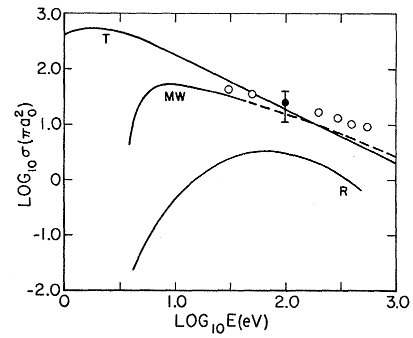

FIG. 2. Comparison of the experimental results with theoretical calculations. The curve T is the classical Thomson cross section, MW is the calculation of McDowell and Williamson, and R is the calculation of Rudge. The dashed line in the MW curve was extended using the logarithmic energy dependence of the cross section, demonstrated in Fig. 1. Born-approximation calculations,[4,5] not shown, are in reasonable agreement with MW in the region of experimental study.

The error bar at 100 eV is a limit of error which is calculated by taking a linear sum of all the estimated limits of systematic error and the statistical errors. The limit of error was found to be (−58%, +38%). The more elaborate calculation of Rudge, in which the Coulomb repulsion between the outgoing electrons is explicitly included in order to obtain the correct threshold behavior, strongly underestimates the cross section. Earlier calculations of Geltman[1] gave an overestimate because of contributions to the cross section from nonvanishing values of $\langle\psi_0|\psi_k\rangle$. Caluclations were made[5] to correct these results for this nonorthogonality. The corrected results are in essential agreement with the Bethe approximation. Similar results in the Born approximation have also been obtained by Smirnov and Chibisov.[4]

Finally, note that good agreement is obtained when experimental cross sections[6,7] for the ionization of He and Li^+, are compared by using classical scaling. The scaled cross section is given by

$$\sigma(E/I)_{\text{scaled}}=\sigma(E/I)(I/I_H)^2,$$

where I is the ionization potential of the atom and I_H is one Ry. The same scaling, applied to the present work in comparison with the He-ionization cross section, places the H^- cross section about a factor of 2 below that for He.

*This research was supported by the Advanced Research Projects Agency (Project DEFENDER) monitored by the U. S. Army Research Office, Durham, under Contract No. DA-31-124-ARO(D)-139.

†Of the National Bureau of Standards and the University of Colorado.

[1]S. Geltman, Proc. Phys. Soc. (London) 75, 67 (1960). The results in this paper are spuriously large because of the use of nonorthogonal approximations for the initial and final atomic wave functions (S. Geltman, private communication).

[2]M. R. C. McDowell and J. H. Williamson, Phys. Letters 4, 159 (1963).

[3]M. R. H. Rudge, Proc. Phys. Soc. (London) 83, 1 (1964).

[4]B. M. Smirnov and M. I. Chibisov, Zh. Eksperim. i Teor. Fiz. 49, 841 (1965) [translation: Soviet Phys.-JETP 22, 585 (1966)].

[5]G. C. Tisone, dissertation, Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado, JILA Report No. 73, 1966 (unpublished).

[6]B. L. Schram, F. J. de Heer, M. J. van der Wiel, and J. Kistemaker, Physica 31, 94 (1964).

[7]W. C. Lineberger, J. W. Hooper, and E. W. McDaniel, Phys. Rev. 141, 165 (1966).

GROUND-STATE SPIN MEMORY IN THE $\bar{E}(^2E)$ LEVEL OF RUBY IN OPTICAL PUMPING VIA THE BANDS

G. F. Imbusch and S. Geschwind
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 20 June 1966)

We wish to present direct experimental evidence of the retention of ground-state spin memory in the $\bar{E}(^2E)$ level of ruby under broadband optical pumping. This has been done by observing a change in the relative populations of the Zeeman components of $\bar{E}(^2E)$ when the populations of the ground-state ($^4A_2$) spin levels are readjusted by microwave saturation.

Recent experiments on excited state epr in the $\bar{E}(^2E)$ state of d^3 ions in corundum have indicated preferential populating of the Zeeman levels of metastable states in pumping through higher broad-absorption bands.[1,2] The evidence for this selective pumping is that one can observe epr in excited states (therefore implying a population difference between the Zeeman levels) in spite of the fact that spin-lattice relaxation between these levels is much slower than the radiative decay. In effect, at very low temperatures the levels cannot thermalize before they radiate and, therefore, must have been preferentially populated. Further corroborating evidence is had from the direct measurement of the intensity of fluorescent lines emanating from these Zeeman levels, which indicated that the excited-state spin temperature differed from the lattice temperature.[3] The existence of this preferential population in the absence of spin-lattice relaxation is not in itself sufficient evidence to indicate a spin memory from the ground state, for such preferential pumping could also come about by thermalization in higher-lying levels which feed the $\bar{E}$ state. In general, one might not anticipate a spin-lattice relaxation time in these higher levels which is fast compared to the feeding time of the metastable state; in ruby, for example, this feeding time from $^4T_2 \rightarrow {}^2E$ has been experimentally shown to be approximately 10^{-7} sec.[4] However, an experiment of the type reported here, where a change in the relative populations of the ground-state Zeeman levels by microwave saturation produces a change in the relative populations of the $\bar{E}$ Zeeman levels, seems to demonstrate unambiguously this spin memory.

In Fig. 1 is shown the Zeeman splitting of the $\bar{E}(^2E)$ and $^4A_2$ states. With H parallel to the c axis, pumping from the $^4A_2$ to $^4T_2$ preserves m_S. Spin memory would now imply that spin selection rules are operative in the multiphonon cascade from the $^4T_2$ band to the final metastable-doublet level without any intervening thermalization in any of the intermediate states. Since the spin-orbit perturbation must be involved in order to make the transition from quartet to doublet, we would anticipate a $\Delta m_S = 0, \pm 1$ selection rule in the $^4T_2 \rightarrow {}^2E$ cascade, considering the admixture of $^4T_2$ to ^2E to first order in spin-orbit coupling. This will, therefore, also be the selection rule from $^4A_2$ to the ^2E via the $^4T_2$. We make no assertions about the details of the cascade process or intermediate states which may be involved, such as the $^2T_1$.[5,6]

The spin populations in the Zeeman levels