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Production of Metastable Hydrogen Atoms by Electron Capture of Protons in a Thick Helium Target

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Abstract. The production of metastable hydrogen atoms by electron capture of protons in a thick helium target is calculated in a three state approximation. Theoretical cross-sections are used for the processes of electron loss from and collisional de-excitation of the excited hydrogen atom, experimental data for the other cross sections involved.

Taking π to be the product of the target length traversed times the target density, the fraction $F_i(\pi)$ of atoms in a state i after passage of the initial beam through the target is given by the solution of the coupled differential equations

$$\frac{dF_i}{d\pi} = - F_i \sum_n \sigma_{i\,n} + \sum_n F_n\, \sigma_{n\,i} \tag{1}$$

where $\sigma_{j\,k}$ is the cross section for transitions from the initial state j to the final state k. Approximate solutions of (1) may be obtained easily by taking account only of a finite number of states. Since the cross sections for electron capture into excited states of hydrogen are rapidly decreasing with increasing principal quantum number it is assumed to be sufficient to retain the hydrogen 2 s-state only. Designating by 0, 1, 2 the H^+, $H(1\,s)$ and $H(2\,s)$ state respectively we find with the initial conditions

$$F_i(0) = \delta_{0\,i} \tag{2}$$

$$\begin{aligned} F_1(\pi) = \frac{e^{-p\,\pi}}{2\,Q} \{[B\,F_{2\infty} - F_{1\infty}\,(A - P + Q)]\,e^{-Q\,\pi} \\ - [B\,F_{2\infty} - F_{1\infty}\,(A - P - Q)]\,e^{Q\,\pi}\} + F_{1\infty} \end{aligned} \tag{3}$$

$$\begin{aligned} F_2(\pi) = \frac{e^{-p\,\pi}}{2\,Q} \{[F_{1\infty}\,G + F_{2\infty}\,(A - P - Q)]\,e^{-Q\,\pi} \\ - [F_{1\infty}\,G + F_{2\infty}\,(A - P + Q)]\,e^{Q\,\pi}\} + F_{2\infty} \end{aligned} \tag{4}$$

$$F_0(\pi) = 1 - F_1(\pi) - F_2(\pi)\,. \tag{5}$$

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The constants are given in terms of the cross sections by

$$\begin{aligned} A &= \sigma_{01} + \sigma_{12} + \sigma_{10} & B &= \sigma_{21} - \sigma_{01} \\ F &= \sigma_{20} + \sigma_{21} + \sigma_{02} & G &= \sigma_{12} - \sigma_{02} \\ P &= \frac{1}{2}\,(A + F) & Q &= \frac{1}{2}\,\{(A - F)^2 + 4\,B\,G\}^{1/2} \\ F_{2\infty} &= \frac{G\,\sigma_{01} + A\,\sigma_{02}}{A\,F - B\,G} & F_{1\infty} &= \frac{\sigma_{01}\,F + \sigma_{02}\,B}{A\,F - B\,G}\,. \end{aligned}$$

The cross sections σ_{01}, σ_{10}, σ_{02}, σ_{12} are taken from experiment [1], whereas σ_{20} and σ_{21} have been calculated. Calculation of σ_{20} is easily done using the classical semi-empirical theory devised by Bates and Walker [2] which is most appropriate for projectiles with a small ionization energy. In fact calculations on electron loss from metastable helium in collisions with molecular hydrogen are in very satisfactory agreement with experiment [3].

The calculation of σ_{21} is a bit more complicated. Remembering the degeneracy of the $2\,p$ and $2\,s$ states in hydrogen it is expected that collisional de-excitation will proceed more rapidly through the two step process

$$H(2\,s) + \mathrm{He} \rightarrow H(2\,p) + \mathrm{He} \rightarrow H(1\,s) + \mathrm{He} + \gamma$$

where γ is the emitted Lyman-α photon, than through the direct $2\,s - 1\,s$ transition. σ_{12} was therefore taken to be the sum of the cross sections for these two reaction paths and was calculated in a $1\,s - 2\,s - 2\,p_0 - 2\,p_1$ close coupling approximation, the helium atom being represented by its static Hartree-Fock potential. Since this four-state approximation does not allow for coupling to the continuum, the results for σ_{21} are probably an overestimate.

Fortunately the final values of $F_2(\pi)$ depend only very weakly on σ_{21}. At the lowest proton energy considered where the influence of σ_{21} is strongest, $F_{2\infty}$ changes only by + 10% putting $\sigma_{21} = 0$. Moreover, this dependence on σ_{21} decreases rapidly with increasing energy and decreasing π. Measurements of $F_2(\pi)$ could therefore be used to derive experimental values of σ_{20}. Alternatively, since σ_{20} can be measured

Table

keV	5	7	9	15	20	25	30	40
$F_{1\infty}$	0.159	0.264	0.337	0.552	0.564	0.582	0.543	0.55
$F_{2\infty}$	0.0049	0.0074	0.0092	0.0093	0.012	0.017	0.019	0.025
A	1.64	2.11	2.36	3.23	3.33	3.29	3.65	2.82
F	2.52	2.75	2.82	2.76	2.52	2.37	2.24	2.01
B	0.036	−0.33	−0.62	−1.69	−1.81	−1.88	−1.96	−1.56
G	0.043	0.046	0.044	0.020	0.0060	0.0036	−0.028	−0.053
P	2.08	2.43	2.59	3.00	2.93	2.83	2.95	2.42
Q	0.44	0.29	0.17	0.15	0.39	0.45	0.74	0.50
σ_{21}	2.22	2.51	2.63	2.64	2.41	2.26	2.13	1.89
σ_{20}	0.30	0.23	0.18	0.11	0.086	0.070	0.058	0.043

directly with good precision, new independent values for σ_{02} which is known only to 50% accuracy could be obtained.

All results including the cross-sections σ_{21} and σ_{20} are collected in the Table. Dimensioned quantities are in units of 10^{-16} cm^2.

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[1] The cross-section taken from the respective reference is given in brackets. P. M. Stier and C. F. Barnett, Phys. Rev. *103*, 896 (1956) (σ_{01}, σ_{10}); V. A. Ankudinov, E. P. Andreev and A. L. Orbeli, Fifth International Conference on the Physics of Electronic and Atomic Collisions, Abstracts of Papers (1967), 312 (σ_{12}); E. P. Andreev, V. A. Ankudinov and S. V. Bobasher, Soviet Physics, JETP *23*, 325 (1966) (σ_{02} above 20 keV); D. Jaecks, B. Van Zyl and R. Geballe, Phys. Rev. *137*, A340 (1965) (σ_{02} below 20 keV).

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