Photodetachment of H^- by Cavity Radiation Update

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December 5, 2004

Abstract

We modify the previous work[1] to allow for electric field effects. Simple estimates from numerical integration give an attenuation length for 600 Gauss in the lab of 1232 km, compared with 1300 km in a field of 0.1 Gauss, both at 8 GeV and 300K. The field effect result is probably an overestimate of the attenuation.

The fraction lost per unit length

We start with a differential expression for the fraction lost per unit length from ref. 1:

$$\frac{d^3 r}{d\Omega d\nu dl} = \frac{L\sigma}{Il} = \frac{(1+\beta\cos\alpha)n(\nu)\sigma(\nu')}{4\pi\beta}, \qquad (1)$$

where $r = R/Il$. $R = L\sigma$, with L the luminosity. $L = c(1+\beta\cos\alpha)\int dVn_{h\nu}n_{ion}$

Putting $\varepsilon = h\nu/E_0, d\Omega = 2\pi\sin\alpha d\alpha$, we have

$$\frac{d^3 r}{d\alpha d\varepsilon dl} = \frac{4\pi E_0^3\varepsilon^2\sin\alpha(1+\beta\cos\alpha)\sigma(\varepsilon', F)}{h^3c^3\beta[\exp(\varepsilon E_0/kT)-1]}, \qquad (2)$$

where the cross section, in general, is a function of the barycentric (the rest frame of the H^- ion) electric field, F, and is evaluated for photon energies in the barycentric frame, so that

$$\varepsilon' = \gamma(1+\beta\cos\alpha)\varepsilon. \qquad (3)$$

The total loss per unit length is then gotten from

$$\frac{dr}{dl} = \int_0^\infty d\varepsilon\int_0^\pi d\alpha\frac{d^3 r}{d\varepsilon d\alpha dl}. \qquad (4)$$

Since $\sigma(\varepsilon', F)$ is likely to be tabulated for any accurate treatment, one must in general proceed from this point by numerical integration. However there are reasonably accurate formulae that describe much of the

[1] H. C. Bryant and G. H. Herling, unpublished, Sept 20, 2004; see also Christopher T. Hill and others, unpublished, Sept 22, 2004. The two treatments give similar results, but differ by factors of the order of 2 depending on the energy.

spectrum that can at least be used to find ball-park estimates. Below we will discuss the remarkable results of Du and Delos[2] as well as a simple approximate analytic description of the shape resonance.

The formulae of Du and Delos

The cross section for photodetachment in an electric field can be written as

$$\sigma(\varepsilon', F) = 0.3604 \frac{F}{(\varepsilon' E_0)^3} a_0^2 D(\phi) , \qquad (5)$$

where F, E_0 are in atomic units, a_0 is the Bohr radius of the hydrogen atom and ϕ is the Aharonov-Bohm[3] electric phase between the two ejected electron trajectories going with and against the external electric field on the ion while it is photodetaching. The formula for $D(\phi)$ depends on the polarization of the light and upon whether we are above or below the zero field threshold for detachment:

For light polarized parallel to the electric field in barycentric frame, above threshold:

$$D(\phi) = \frac{1}{4\pi}(\phi + \cos\phi) , \qquad (6)$$

For light polarized perpendicular, above threshold:

$$D(\phi) = \frac{1}{4\pi}\left(\phi - \frac{1}{12\pi}\frac{\sin\phi}{\phi}\right) . \qquad (7)$$

In these cases, $\phi = \frac{4\sqrt{2}}{3}\frac{[E_0(\varepsilon' - 1)]^{3/2}}{F}$ in atomic units.

In our numerical examples we will only examine the first case as an upper limit. For the below threshold region (zero when no field is present) we use

$$D(\phi') = \frac{1}{8\pi}\exp(-\phi') \qquad (8)$$

where $\phi' = \frac{4\sqrt{2}}{3}\frac{[E_0(1 - \varepsilon')]^{3/2}}{F}$.

The two analytic forms to not join smoothly at threshold, and Du and Delos provide a numerical table. For our example we are ignoring this discontinuity at threshold. The below threshold behavior is somewhat controversial, in any case.[4] A more elaborate and accurate numerical calculation is planned.

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[2] M. L. Du and J. B. Delos, Phys Rev A **38**, 5609 (1988), Phys Lett A **134**, 476 (1989).

[3] Y. Aharonov and D. Bohm, Phys Rev **115**, 485 (1959)

[4] H. C. Bryant, "A Three-Body System in Electric Fields", Invited Paper presented at the International Conference on Electronic , Atomic and Photonic Collisions (ICPEAC XXII), Santa Fe, New Mexico, 18-24 July, 2001, in Ballroom, La Fonda Hotel, 15:15, 24 July 2001. Paper based on this talk published in Book of Invited Papers."Photonic, Electronic and Atomic Collisions",Burgdorfer, Cohen, Datz and Vane, Eds., Rinton Press , Princeton NJ, 2002, pp517-524.

Introducing the shape resonance

The shape resonance[5], a doubly-excited feature involving an electron bound to the first excited state of hydrogen can be added by hand to this cross section to test whether it makes any contribution to the stripping. (As we shall see below it does not.)

The resonance may be described reasonably well using the Fano profile[6], modified to be added to the Du-Delos cross section in the region of excitation of 11 eV.

$$\sigma_S = \sigma_a \left[\frac{(Q+\eta)^2}{(1+\eta^2)} - 1 \right] \qquad (9)$$

where $\eta = 2(E - E_s)/\Gamma$ and $E = \varepsilon E_0$, the photon energy.
For no electric field these parameters are given by

$$\begin{aligned} E_S &= 10.97076\_eV \\ \Gamma_0 &= 15.1850\_meV \\ Q &= 4.7548 \\ \sigma_a &= 0.12511\_a_0^2 \end{aligned} \qquad (10)$$

This remarkable resonance broadens in the presence of an electric field. To model this in a simple way we write

$$\Gamma = \Gamma_0 + 5.29x10^{-8} F\ , \qquad (11)$$

with the field given in V/cm. Also to prevent the cross section from going negative, we cut it off for $\eta < -Q/2$.

With these formulas we have reeached some numerical conclusions using an Excel spread sheet.

Conclusions

The attenuation length for zero field at 8 GeV in a 300K cavity is about 1300 km. This is near the minimum found around 25 GeV. We can put an upper limit on the additional attenuation due to a 600 Gauss transverse field in the lab, giving an attenuation length of 1258 km. The attenuation can be diminished by lowering the temperature of the beam pipe.

Acknowledgement

We thank Gary Herling, Weiren Chou, Bill Foster and Chris Hill for discussions and Tom Hess for his technical support.

[5] H. C. Bryant et al, Phys Rev A **27**, 2889 (1983)
[6] U. Fano, Phys. Rev. **124**, 1866 (1961)

Figure 1. Photodetachment cross section in the threshold region with 0.1 Gauss in lab at 8 GeV, as given in the barycentric frame (H^- rest frame). The photon energies are those in the lab for head-on collision with H-, so that the threshold is 0.75 eV in the barycentric frame. kT of the black-body spectrum at 300 K is 0.033 on this scale.

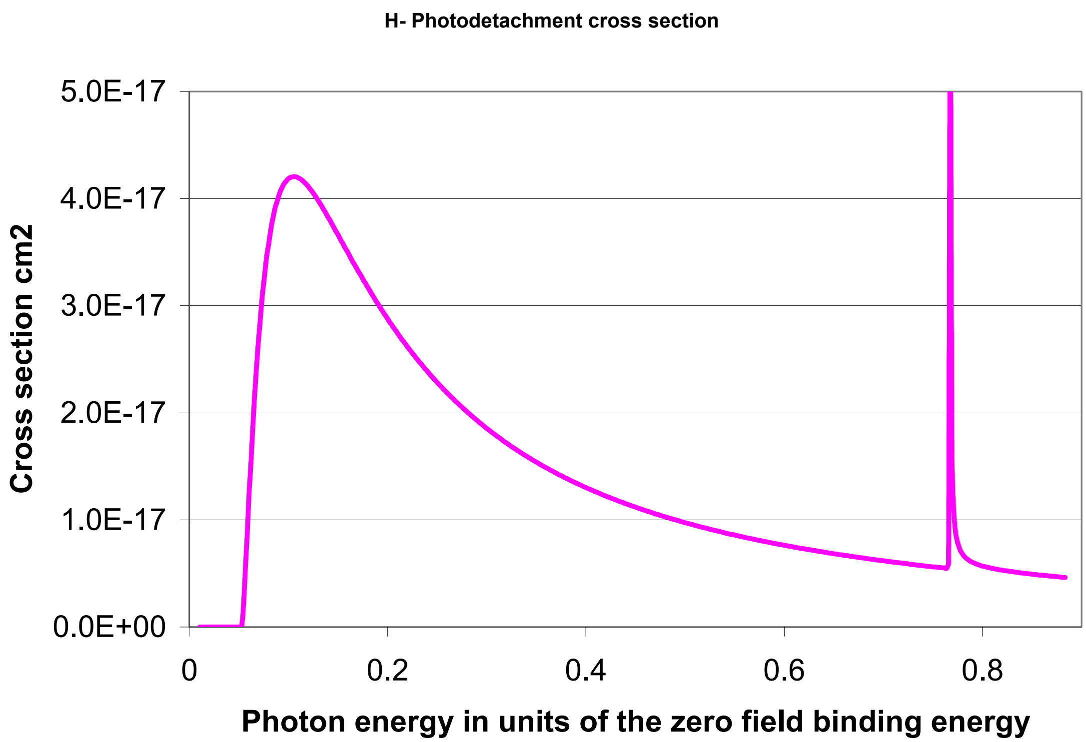

Fig 2. Same as Fig 1, showing the shape resonance. The full height of the shape resonance is not shown. The presence of the resonance has no appreciable effect on the attenuation length. L=1300 km

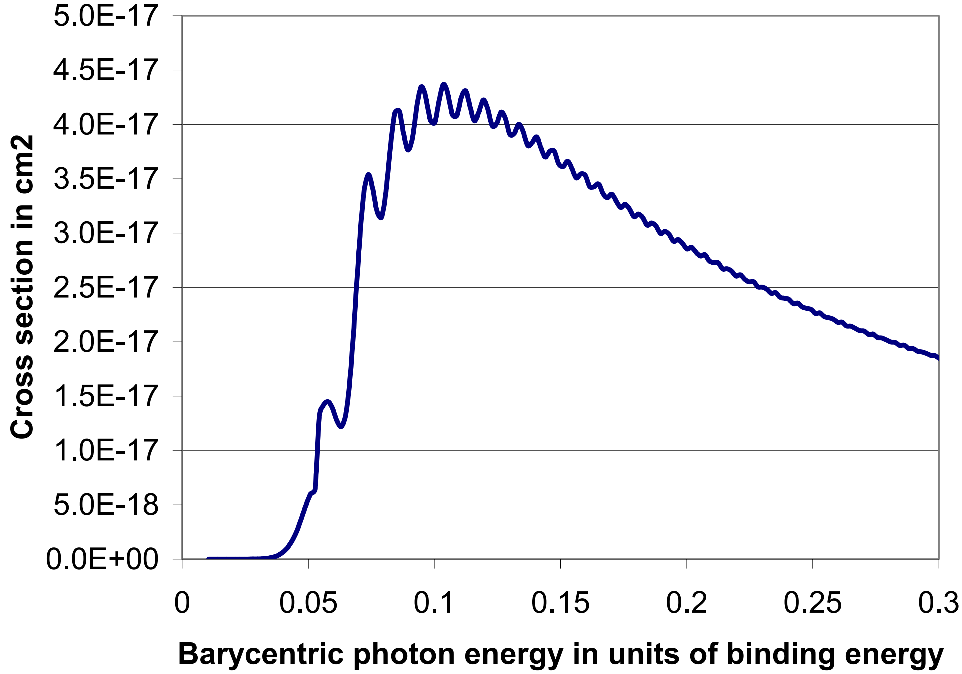

Fig 3. Same as above, with lab field 600 Gauss (1.7 MV/cm). The cross section near threshold is obtained using the Du Delos analytic functions, which are discontinuous at the zero-field value. This cross section is for the polarization of the incident light parallel to the barycentric field direction. We have not considered any effect due to the barycentric magnetic field of 5700 Gauss.

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L=1258 km.

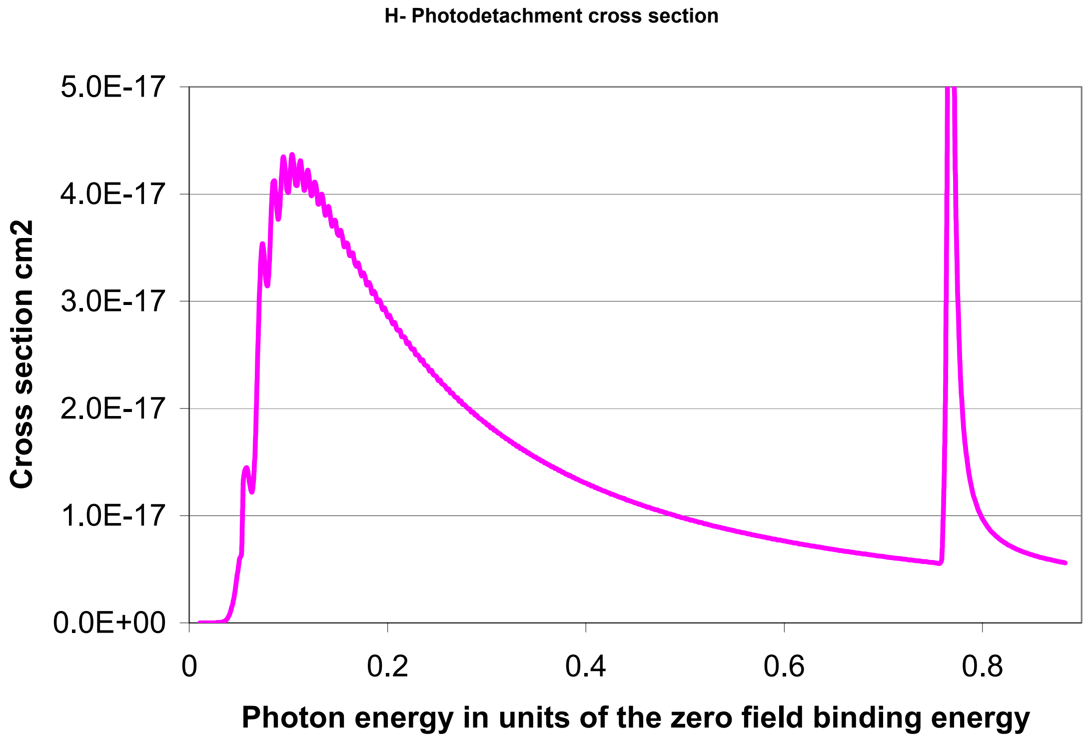

Fig. 4. the photodetachment cross section in the barycentric frame in 600 Gauss in lab (1.7 MV/cm in CoM). In the barycentric frame the light is polarized parallel to the electric field direction. So-called π polarization. The shape peak should be the same value as in zero field case. In a field the width of the shape resonance increases. L=1258 km, 8 GeV, 300K cavity radiation.

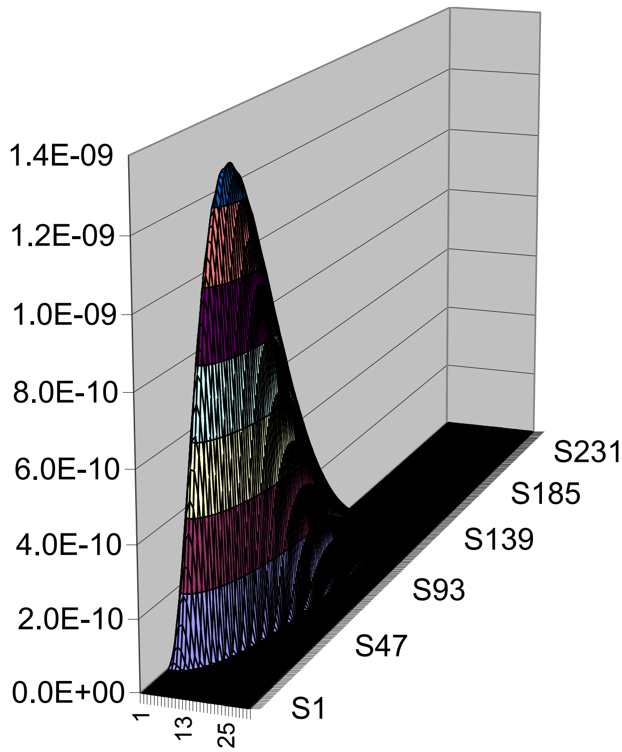

Figure 5 is a 2D histogram of the Excel cell values giving contributions to the detachment rate for as function of lab photon energy (in units of the binding energy, .7542 eV) along S1..S231, and laboratory impact angles 1..25. The beam energy is 8 GeV and the transverse magnetic field in the lab is 0.1 Gauss. T=300 K. The sum of the cells gives an attenuation length of 1300 km. The shape resonance makes no appreciable contribution.

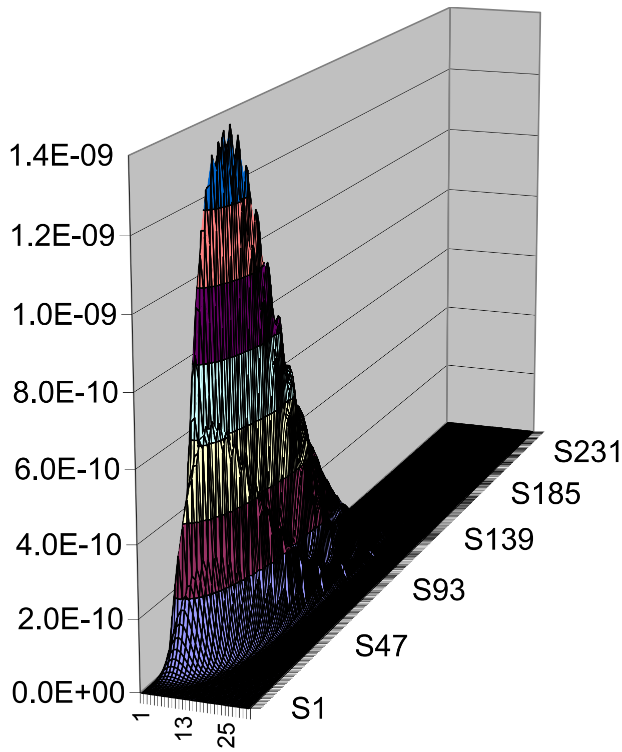

Figure 6 is the same as the 5 above except the transverse magnetic field in the lab is 600 Gauss (1.7 MV/cm in the CoM). The sum of the cell values gives an attenuation length of 1232 km. The shape resonance makes no appreciable contribution. The difference between field on and off is due to the threshold region

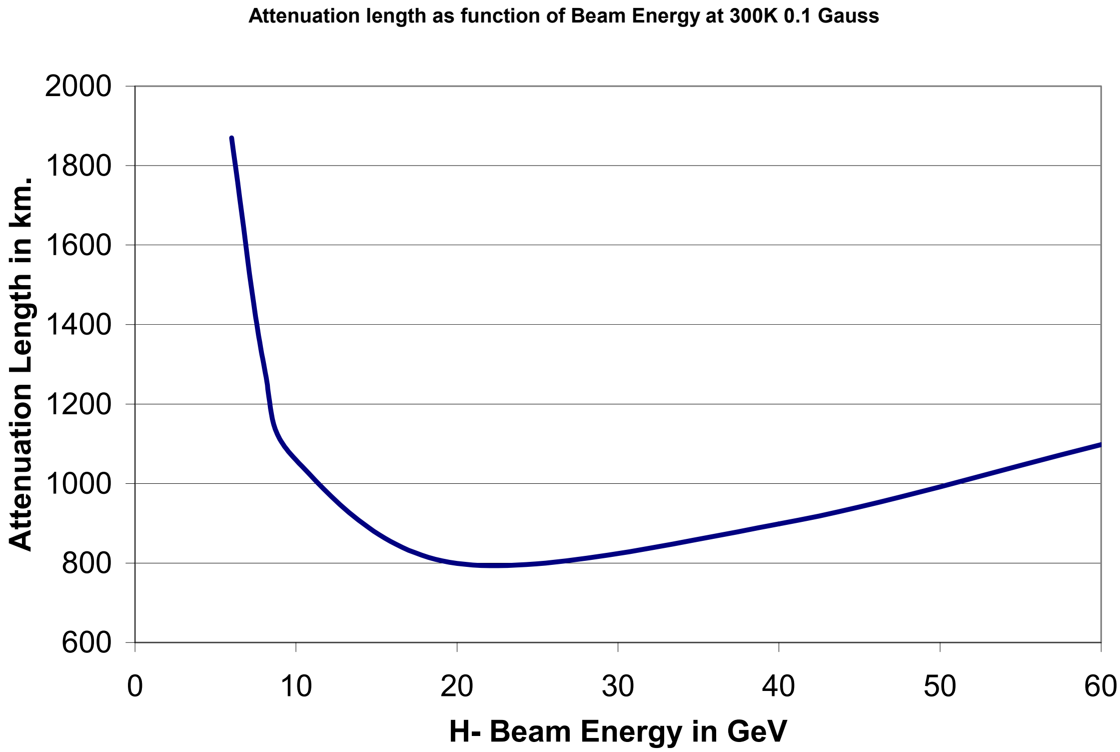

Figure 7 displays the attenuation length as function of the H- beam energy in 0.1 Gauss lab B field at 300K.

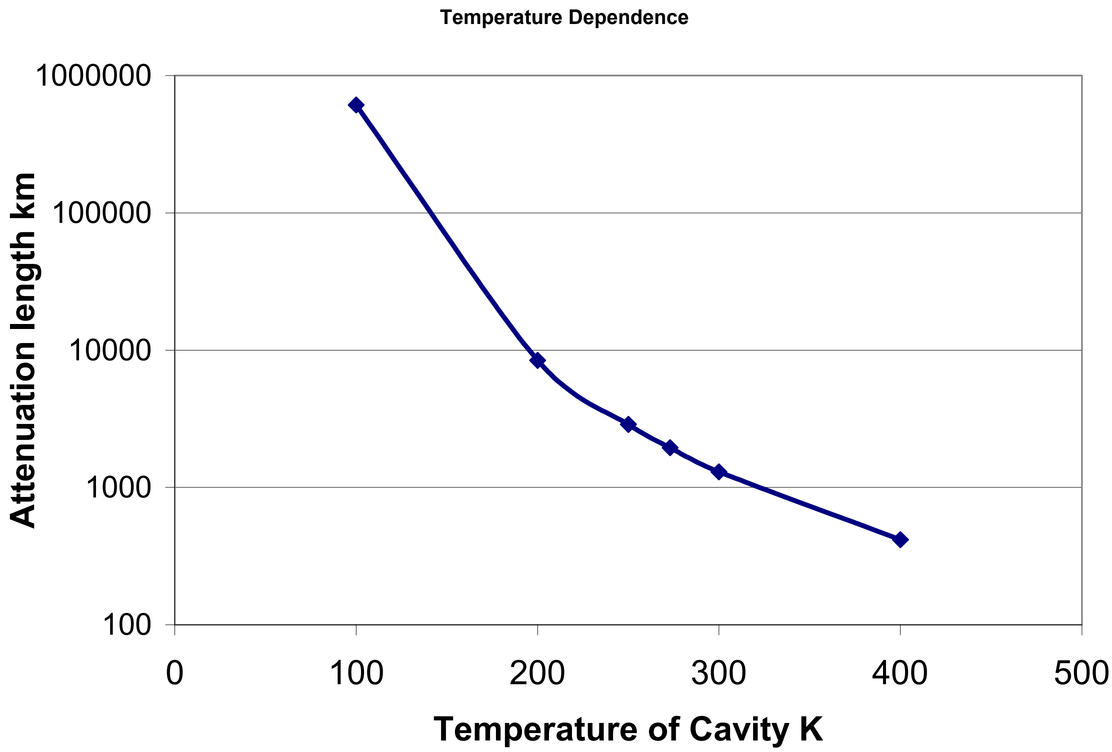

Fig 8. Temperature dependence of attenuation length of 8 GeV H- beam in 0.1 Gauss Lab field.