H^- stripping in collisions with low-energy $\bar{p}$ and H^-

G. Fiorentini
Istituto Nazionale di Fisica Nucleare and Istituto di Fisica, I-56100 Pisa, Italy

R. Tripiccione
Scuola Normale Superiore and Istituto Nazionale di Fisica Nucleare I-56100 Pisa, Italy
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Electron detachment of H^- by impact of low-energy antiprotons and H^- is studied. Detachment cross sections for relative velocities $v \leq 0.1\alpha c$ are evaluated with the use of several approximations. Results of different methods of calculation are consistent with each other. Cross sections of about 10^{-14} cm^2 are obtained just above the detachment threshold.

As an extension of the low-energy antiproton ring (LEAR) project at CERN, a scheme of corotating $\bar{p}$ and H^- beams is being considered.[1] By means of electron cooling, the momentum spread of the particles in the beam will be reduced to $\Delta P/P \sim 10^{-4}$ in order that it is possible to produce p-$\bar{p}$ atomic systems *in vacuo* by the Auger process.[2] In view of discussing the feasibility of such a scheme and of planning optimal machine parameters, it is important to study the processes of electron detachment of H^-, since these are the main source of H^- beam loss. Electron detachment arising from interactions with the residual gas in the pipe and with the driving magnetic field have been discussed elsewhere.[3] We focus here on beam-beam interactions, i.e., the reactions:

$$H^- + \bar{p} \rightarrow H + e + \bar{p} \ , \tag{1}$$

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

at relative velocity $v \leq 0.1\alpha c$, corresponding to the operation conditions planned for LEAR.

Since v is small in comparison with the electronic velocity ($v_e \sim \alpha c$), the detachment problem can be assumed to occur in a slowly varying electric field (adiabatic approximation). The typical internuclear distance of the problem R_0 is fixed by requiring that the Coulomb energy between the H^- and the other particle equals the electronic affinity of the H^- ion, $E_b = 0.754$ eV. Hence

$$R_0 = e^2/E_b = 36a_0 \ . \tag{3}$$

This distance being much larger than the H^- linear dimension ($\langle r \rangle \simeq 2.7a_0$), reactions (1) and (2) are essentially the same. For definiteness we consider reaction (1). Moreover, classical mechanics can be used to describe the relative motion of the H^- and $\bar{p}$ since high values of angular momentum are relevant to the problem:

$$L_0 = \tfrac{1}{2} m_p v R_0 \simeq 1000\hbar \text{ at } v = 0.05c \ . \tag{4}$$

A first rough estimate of the detachment cross section σ can be obtained by very simple considerations. As the antiproton and the H^- approach each other, the internal energy of the H^-, $E(R)$, is raised until a distance R_d is reached such that $E(R_d) = 0$. At distances $R < R_d$, the H^- system is unstable since it is degenerate with the dissociated $H + e$ states. We assume that the detachment probability P is unity if H^- and $\bar{p}$ get closer then R_d, independently of details of motion; otherwise $P = 0$. The detachment cross section is thus determined by (i) calculating R_d and (ii) evaluating the largest impact parameter $b_{\max}$ such that $\bar{p}$ and H^- can reach R_d. The cross section is then

$$\sigma = \pi b_{\max}^2 \ . \tag{5}$$

Neglecting terms which are $O(a_0^4/R_d^4)$, R_d is determined by

$$E(R_d) = -E_b + e^2/R_d = 0 \ . \tag{6}$$

This gives $R_d = R_0$.

The colliding particles have to overcome the Coulomb and centrifugal barrier in order to reach R_d; hence

$$b_{\max} = \begin{cases} 0 & \text{for } m_p v^2/4 < E_b \ , \\ R_0[1 - 4E_b/(m_p v^2)]^{1/2} & \text{otherwise} \ . \end{cases} \tag{7}$$

The resulting cross section is plotted in Fig. 1(e). One sees that σ takes on large values, of order 10^{-14} cm^2, soon after the threshold.

In order to have a more accurate determination of the detachment probability P we resort to a WKB approximation for the electronic degrees of freedom,

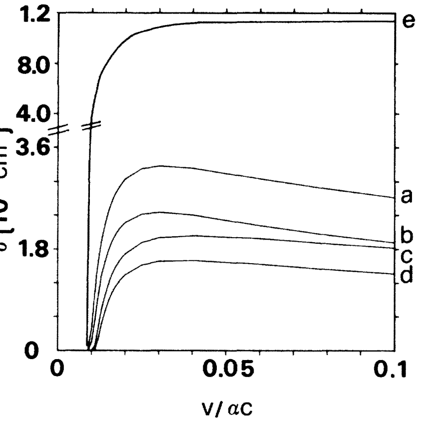

FIG. 1. Detachment cross section σ as a function of the relative velocity v, calculated from (a) Eq. (9) with A as in Ref. 4, (b) Eq. (9) with $A \to A_{\text{eff}} = 0.57A$, (c) Eq. (14) with A as in Ref. 4, (d) from Eq. (14) with $A \to A_{\text{eff}} = 0.57A$, and (e) Eq. (5).

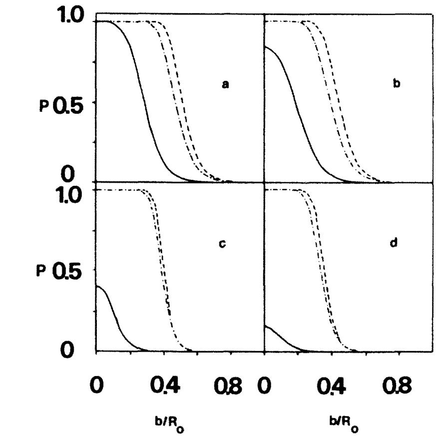

FIG. 2. Detachment probability $P(b,v)$ [Eq. (11)] as a function of b/R_0. (a), (b), (c), and (d) refer to the same formulas as in Fig. 1. Solid line is for $v = 0.011\ \alpha c$, dashed line for $v = 0.025\alpha c$, dashed-dotted line for $v = 0.1\alpha c$.

in the frame of an effective single-particle scheme.[4] We treat the electric field generated by the $\bar{p}$ as approximately uniform over the size of the H^- system with a strength $\bar{F}$ given by $\bar{F} = e/R^2$, R being the distance between the colliding particles. This approximation is justified at the typical distances of the detachment process R_d since

$$\Delta F/F \simeq \langle r \rangle / R_d \simeq 0.1 \ . \tag{8}$$

Within these approximations, the detachment probability per unit time in a field with strength F is[5]

$$W(F) = \frac{A^2}{2}(2m_e E_b)^{-1/2} eF \times \exp\left[-\frac{4E_b(2m_e E_b)^{1/2}}{3\hbar eF}\right] , \tag{9}$$

where A is the normalization factor for the asymptotic electron wave function

$$\psi_{\text{as}}(r) = A(k/2\pi)^{1/2} \exp(-kr)/r \ , \quad k = (2m_e E_b)^{1/2}/\hbar \ . \tag{10}$$

We take $A = 2.65$ as in Ref. 4.

The detachment probability for a $\bar{p}$-H^- collision at impact parameter b is then

$$P(b,v) = 1 - \exp\left[-\int W(\bar{F})\,dt\right] , \tag{11}$$

where the integral is performed along the classical trajectory determined by the impact parameter b and the velocity v. The probability distribution is shown in Fig. 2(a) for several values of v. The cross section is given by

$$\sigma(v) = \pi \int_0^\infty P(b,v) b\,db \tag{12}$$

and is displayed in Fig. 1(a). It is somewhat smaller then was found in the previous model, as it should since the probability for transitions to the dissociated states depends on the interaction time, whereas in the model considered before we had taken $P = 1$ for $b \le b_{\max}$ independently of the interaction time. This is also the reason for the slow decrease of the cross section at the higher velocities, where the collision time is shorter. It is clear however that for $v > 0.1\alpha c$ diabatic mechanisms contribute significantly to the electron detachment cross section.

The validity of using the WKB and effective single-particle approximations in this problem can be checked by means of an analysis of experimental data on H^- lifetime

$$\tau(F) = 1/W(F)$$

in electric fields of the order of 2 MV/cm.[6] This is in fact the same range of field strength which is relevant to our problem ($e/R_d^2 \sim 2$ MV/cm). As shown in Fig. 3, Eq. (9) accurately reproduces the shape of the experimental curve, but overestimates the decay probability by a factor of about 3. We feel this is a consequence of the limitations of the effective single-particle approximation, which can be overcome empirically by adjusting the normalization of the asymptotic wave function:

$$A \to A_{\text{eff}} = 0.57A \ . \tag{13}$$

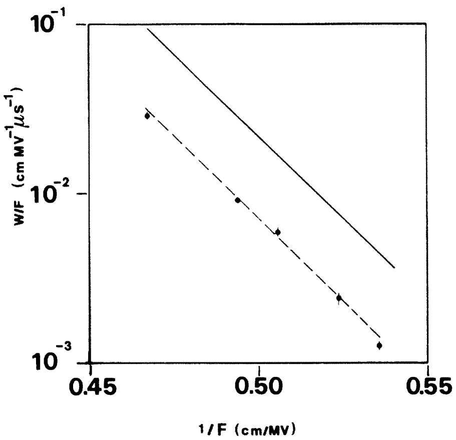

FIG. 3. Comparison of experimental data on $\tau(F)=1/W(F)$ with the WKB prediction, Eq. (9). Experimental points are from Ref. 6. Solid line is calculated from Eq. (9) with $A=2.65$, dashed line from the same equation with $A\rightarrow A_{\rm eff}=1.50$.

We have performed the same calculations outlined in Eqs. (9), (11), and (12) after replacing A with $A_{\rm eff}$. The results are shown in Figs. 2(b) and 1(b). Cross sections are reduced by about 15%, which is however a rather small effect as compared to the large difference between A and $A_{\rm eff}$.

The uniform field approximation used so far can be released. The motion of an electron in the field of two Coulomb centers can be separated by using elliptical coordinates, and WKB expressions for the detachment probability can be derived.[5] W can be expressed in terms of the separation distance R as follows:

$$W=\frac{A^2}{2}(2m_eE_b)^{-1/2}\frac{e^2}{R^2}\times\exp\left[-\frac{2}{\hbar}(2m_eE_b)^{1/2}Rf(RE_b/e^2)\right],$$
$$f(x)=(\sin^{-1}\sqrt{x})/[x(1-x)]^{1/2}-1\,. \tag{14}$$

By using this presumably more accurate expression, we have evaluated the detachment probabilities and cross section with the same technique as in the uniform field case. The results, presented in Figs. 2(c) and 1(c), show that the cross section is slightly smaller than in the homogeneous field approximation. This occurs since the perturbing field vanishes at large distances.

On the grounds of the foregoing discussion, we also performed a calculation with A replaced by $A_{\rm eff}$ in Eq. (14), yielding the results shown in Figs. 2(d) and 1(d).

In conclusion, we evaluated the detachment cross section of H$^-$ by using several methods of increasing complexity and accuracy. The stability of results obtained with different approximations is remarkable. This gives confidence about the reliability of the methods of calculation. It would be interesting to have direct experimental information on the process before LEAR phase II is built. This could be obtained by measurements with crossing H$^-$ beams, using techniques in principle similar to those considered in Ref. 7 to study H$^-$ dissociation by proton impact.

It is a pleasure to acknowlege discussions on this matter with Ugo Gastaldi and Dieter Möhl.

[1]See, for example, U. Gastaldi and R. Klapisch, in *Proceedings of the LXXIX Course of the International School of Physics, "Enrico Fermi,"* edited by A. Molinari (Società Italiana di Fisica, Bologna, Italy, 1981).

[2]L. Bracci, G. Fiorentini, and O. Pitzurra, Phys. Lett. 85B, 280 (1979).

[3]U. Gastaldi, CERN $p\bar{p}$ note 32, 1977 (unpublished).

[4]T. Ohmura and H. Ohmura, Phys. Rev. 131, 1132 (1963).

[5]B. M. Smirnov and M. I. Chibisov, Zh. Eksp. Teor. Fiz. 49, 841 (1965) [Sov. Phys.–JETP 22, 585 (1966)].

[6]G. M. Stinson, S. C. Olsen, W. J. McDonald, P. Ford, D. Axen, and E. W. Blackmore, Nucl. Instrum. Methods 74, 333 (1969).

[7]B. Peart, R. Grey, and K. T. Dolder, J. Phys. B 9, 3047 (1976).