Electron Detachment from 20-MeV D^- Ions by a Magnetic Field

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The probability of electron detachment from 20-MeV D^- ions by the Lorentz force of a magnetic field has been measured as a function of field strength. For a transit time through the magnetic field of $\approx 5\times10^{-10}$ sec, the detachment process becomes important at an equivalent electric field, $\mathcal{E}=\gamma(\mathbf{v}/c)\times\mathbf{B}$, of about 3.2×10^6 V/cm and is essentially complete at 4.2×10^6 V/cm. The results are in agreement with calculations by Hiskes and Khoe.

I. INTRODUCTION

A PARTICLE traversing a magnetic field $\mathbf{B}$ with a velocity $\mathbf{v}$ experiences an electric field $\mathcal{E}=\gamma(\mathbf{v}/c)\times\mathbf{B}$, where $\gamma=(1-v^2/c^2)^{-1/2}$. If the electric field in the rest frame is sufficiently strong, one or more electrons may be detached from an atom or ion.[1] The present paper describes a measurement of the detachment probability for negative hydrogen ions, in our case D^-.

Accelerator designers have discussed the desirability of accelerating negative hydrogen beams because of the relative ease of extraction from circular accelerators after stripping to neutral or positive ions.[2–4] The loss of ions within the cyclotron or synchrotron through collisions with the background gas has also been considered[1,4] and found to be a real but probably manageable problem. A more serious limitation to the development of high-energy negative hydrogen beams was suggested by Khuri,[1] who showed that the $\gamma(\mathbf{v}/c)\times\mathbf{B}$ equivalent electric field of a typical circular accelerator would detach an electron from a negative hydrogen ion by the time that it reached a kinetic energy of perhaps 30 MeV.

The high-field short-lifetime experiments described here were undertaken as a check on the Khuri theory; at the same time Hiskes[5] refined Khuri's calculations. The recent demonstration that a high-quality, if low-energy proton beam could be extracted from an H^- cyclotron[6] has renewed interest in the practical implications of electron detachment by the Lorentz force of a magnetic field. These implications for cyclotrons and synchrocyclotrons have been discussed by Judd.[7]

We note in passing that the detachment of electrons from negative helium ions in a static electric field has been measured by Riviere and Sweetman[8] and the detachment of electrons from neutral hydrogen atoms by static electric or $(\mathbf{v}/c)\times\mathbf{B}$ fields has been calculated[9] or measured[10–12] by several groups.

II. THEORY

In this section we will outline Khuri's intentionally rough, one-dimensional WKB calculation to demonstrate the physical process, and present the results of Hiskes' more precise calculations for comparison with the experiment.

Khuri assumed that the effective potential energy of the extra electron in the H^- ion is given by

$$V(x)=-Ze^2/x-e\mathcal{E}x, \tag{1}$$

where $\mathcal{E}=\gamma(\mathbf{v}/c)\times\mathbf{B}$, and x is the displacement of the electron from the center of mass. The first term is a Coulomb potential in which Z is assigned the value $Z=0.24$ (instead of $Z=1$) to make the binding energy of the extra electron equal to 0.76 eV. The potential energy is sketched in Fig. 1. The top curve is for the case in which there is no external field and the detachment lifetime τ is infinite. The bottom curve is for the maximum energy in the Princeton-Pennsylvania proton

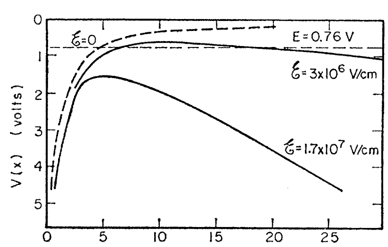

FIG. 1. The potential energy of the second electron versus its displacement from the center of the H^- ion, according to Khuri's model (Ref. 1) for equivalent electric field values of 0, 3×10^6, and 1.7×10^9 V/cm.

[1] N. N. Khuri, Palmer Physical Laboratory, Princeton University Report PPAD 124, 1956 (unpublished).

[2] J. H. Fremlin and V. M. Spiers, Proc. Phys. Soc. (London) **A68**, 398 (1955).

[3] G. K. O'Neill, in *Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva* (CERN, Geneva, 1956), Vol. 1, p. 64.

[4] B. T. Wright, Arch. Math. Naturvidenskab **54**, 8 (1957).

[5] John R. Hiskes, Lawrence Radiation Laboratory, Livermore, California (private communication).

[6] M. E. Rickey and W. R. Smythe, Nucl. Instr. Methods **18** and **19**, 66 (1962).

[7] David L. Judd, Nucl. Instr. Methods **18** and **19**, 70 (1962).

[8] A. C. Riviere and D. R. Sweetman, Phys. Rev. Letters **5**, 560 (1960).

[9] John R. Hiskes, Nucl. Fusion **2**, 38 (1962).

[10] A. C. Riviere and D. R. Sweetman, in *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich, 1961* (North-Holland Publishing Company, Amsterdam, 1962), Vol. II, p. 1236.

[11] S. N. Kaplan, G. A. Paulikas, and R. V. Pyle, Phys. Rev. Letters **9**, 348 (1962).

[12] A. H. Futch and C. C. Damm, University of California Lawrence Radiation Laboratory Report UCRL-10607, 1963, p. 30 (unpublished).

synchrotron (3 BeV in a 14-kG field); the second electron is not bound at all. The central curve is an example of a case in which the second electron is classically bound but can escape with a mean life τ by barrier penetration. In the absence of a good estimate of the H^- polarizability Khuri obtained a lower limit for τ from the barrier penetration probability formula,

$$P=\exp\left[-\int_{x_1}^{x_2}\left(\frac{8m}{\hbar^2}[V(x)-E]\right)^{1/2}dx\right],$$

and a vibration frequency for the electron of 10^{14} sec^{-1}. Thus, $\tau\approx 1/(10^{14}P)$. A curve of lifetime versus electric field calculated according to the above model is labeled K in Fig. 2.[13]

Hiskes[5] has made a three-dimensional WKB calculation using a value of 2.5×10^{15} sec^{-1} for the orbital frequency and correcting for the effective solid angle for barrier penetration (one tenth of the total solid angle, for the conditions of our experiment). He obtained curve C of Fig. 1 in Ref. 7 and Fig. 2 in this paper by using a shielded potential,

$$V(r)=-\frac{e^2}{a_0}\left(1+\frac{a_0}{r}\right)^{-2r/a_0}+\tfrac{1}{2}\alpha_{H^-}\mathcal{E}^2-e\mathcal{E}r, \qquad (2)$$

where a_0= Bohr radius. Pekeris' value[14] for the electron binding energy, $E=0.755$ eV, and Schwartz's value[15] for the polarizability of the H^- ion, $\alpha_{H^-}=212a_0^3$, were used in the calculation.

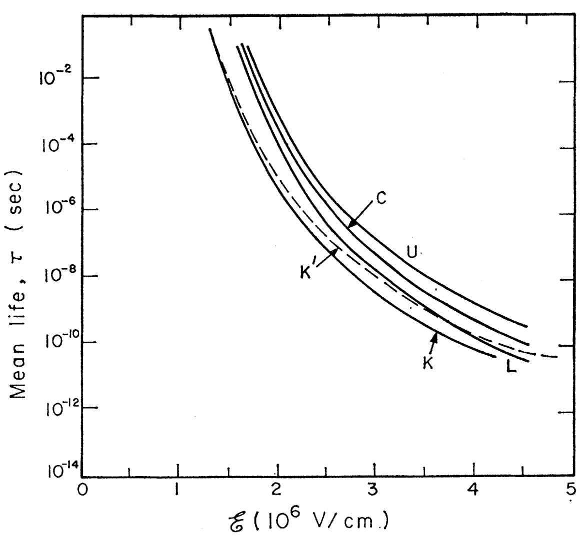

FIG. 2. The mean life for detachment versus electric field. Curve K is based on Khuri's original estimate (Ref. 1); K' is a calculation by Khoe (Ref. 16) (see text). Curve C is Hiskes' shielded potential calculation (Ref. 5), using Eq. (2). Curves U and L are upper and lower limits on curve C.

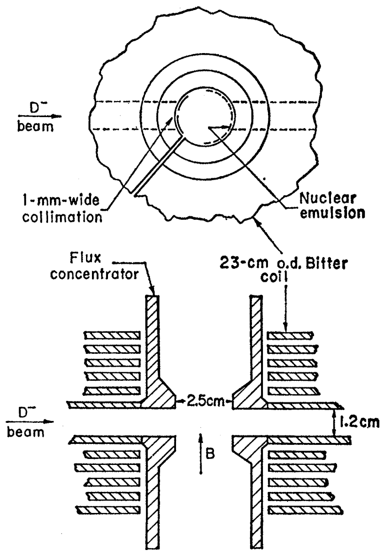

FIG. 3. The experimental arrangement.

Curves U and L represent the estimated limits of uncertainty of this calculation (a factor of three in τ). It is also possible to include a term in $V(r)$ to account for the polarization of the neutral core of the H^- ion by the second electron, $-\frac{1}{2}\alpha_H(e^2/r)^2$, where $\alpha_H=(9/4)a_0^3$. The effect of this term would be to reduce by a small amount the electric field required for detachment in a given time.

Also shown in Fig. 2 is a recent unpublished calculation by Khoe,[16] who used a square-well potential.

III. EXPERIMENTAL PROCEDURE

The experiment was performed in a pulsed magnetic field, with nuclear emulsions as particle detectors. The 20-MeV D^- beam[17] of the Berkeley heavy-ion linear accelerator (Hilac) was bent through a 15-deg angle to remove the products of gas stripping in the accelerator and the beam transport system. Single beam pulses with a full width of 50 μsec were obtained by adjusting the timing of the pulsed source and the rf excitation of the Hilac. The negative ions entered the 430-μsec quarter-cycle-time magnetic field at its peak; the magnetic field was, therefore, constant in time to within 1% during the beam pulse.

The magnet[18] is a high-field coil of Bitter design, potted in an epoxy resin so that it could be operated in a vacuum ($\approx10^{-5}$ mm Hg), and is powered by a small capacitor bank (4000 μF, 5000 V). The magnetic field obtainable in the original 5- cm-diam bore was sufficient to cause detachment according to the first estimates, but no breakup was observed. We therefore inserted a flux concentrator with a bore 2.5 cm in diameter into the magnet, thus raising the maximum field to 160 kG.

[13] The curve labeled K in Fig. 1 of Ref. 7 is apparently based on other numbers than those that were used by Khuri (Ref. 1).
[14] C. L. Pekeris, Phys. Rev. **112**, 1649 (1958).
[15] C. L. Schwartz (unpublished) quoted in Ref. 7.
[16] T. K. Khoe, Argonne National Laboratory Report ANLAD-72, 1962 (unpublished).
[17] The experiment was carried out with D^- rather than with H^- ions because the Hilac rf stability is poor at low gradients.
[18] We are very grateful to Harold P. Furth for lending us the basic magnet structure.

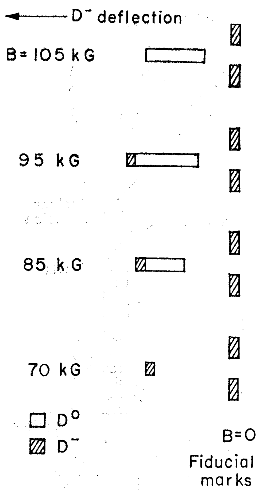

FIG. 4. Appearance of the data on an emulsion. The shaded regions have higher densities and are primarily D^- ions.

The beam entered the magnet perpendicular to the field through a hole 1.2-cm high and 1.9-cm wide. Data were recorded with 50-μ C-2 nuclear emulsions that followed the contour of the magnet bore (Fig. 3). A 1-mm-wide slit, parallel to the magnetic axis, collimated the beam at the beginning of the high-field region. External to the Bitter magnet was a movable set of slits that collimated the beam parallel to the magnetic field.

Before each exposure a pair of fiducial marks was put on the emulsion by pulsing the beam with zero magnetic field. A single deflected pulse was then recorded at high magnetic field, giving the appearance shown schematically in Fig. 4. The strength of the field during each pulse was monitored by integrating the output of a single-turn loop which was solidly attached to the flux concentrator. The beam pulse (monitored by a plastic scintillator) and the magnetic field pulse were simultaneously displayed on separate sweeps of an oscilloscope.

A small calibrated search coil was used to map the magnitude and shape of the field before, during, and after the accelerator run.[19] The field was flat to within 1% over a 1-cm path at the center of the magnet and dropped to 90% of the central value at a radius of 1.1 cm (Fig. 5). (From Fig. 2 we see that a 10% change in field is approximately equal to a factor of two change in the detachment lifetime.)

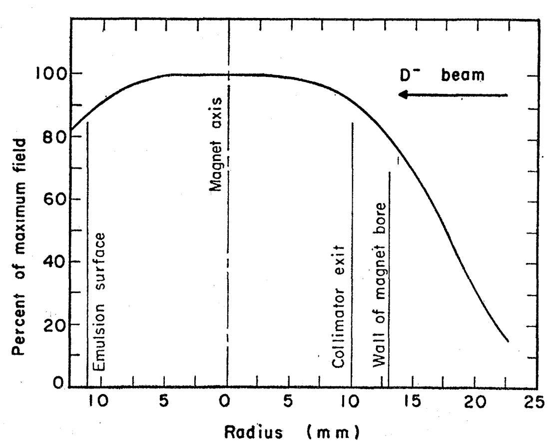

FIG. 5. The shape of the magnetic field in the bore of the magnet and in the hole through the flux concentrator.

A semiquantitative measurement of the electron detachment as a function of magnetic field was obtained by scanning the emulsions with a low-power microscope.[20] In this way we estimated that clear-cut evidence of stripping was observed at 82±4 kG, and that the breakup was complete at 100±5 kG. We interpolated that the D^- beam would be reduced by a factor of e at a magnetic field of perhaps 94 kG, which is equivalent to an electric field of 4.2×10^6 V/cm (1 kG is equivalent to 4.44×10^4 V/cm in this experiment). This rather im-

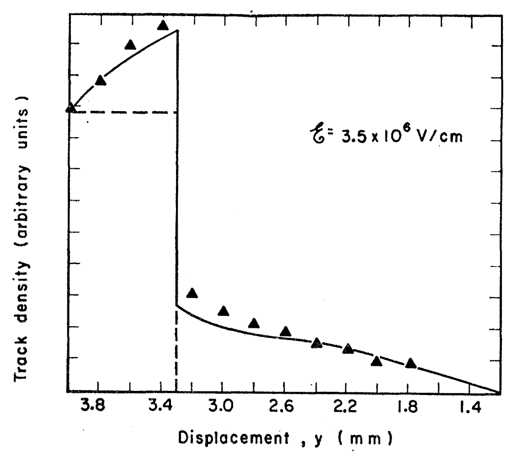

FIG. 6. Typical determination of track density versus displacement on the emulsion. The method of calculation of the solid curve is described in the text. The rectangle enclosed by dotted lines represents D^- ions; the two approximately triangular sections D^0 atoms. The experimental points represent a total of 3990 tracks.

precisely determined point falls on Hiskes' curve C, Fig. 2.

The emulsions were then scanned at higher power and the tracks were individually counted. A typical profile is shown in Fig. 6. Detachment probabilities (Fig. 7) were obtained by dividing the track-density profiles into charged and neutral components. The vertical bars represent estimated limits on the uncertainty of the method of analysis; the horizontal bars give the estimated uncertainty in the absolute calibration of the magnetic field. Both kinds of errors are chiefly systematic rather than statistical.

For comparing the experimental results with theory the equivalent electric field, $\mathcal{E}$, in the bore was approxi-

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[19] We wish to thank Joseph H. Dorst and members of his magnet testing group for the calibration of our search coil.

[20] R. V. Pyle, S. N. Kaplan, and G. A. Paulikas, Bull. Am. Phys. Soc. 7, 487 (1962).

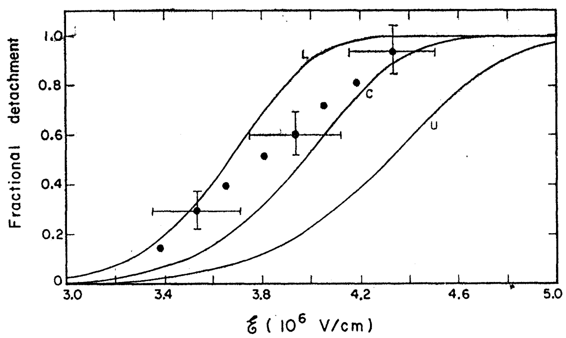

FIG. 7. The solid lines give the fractional detachment versus equivalent electric field calculated as described in the text. The abscissa represents the equivalent electric field at the center of the magnet.

mated by (cf., Fig. 5):

$$\begin{aligned} &0\leqslant r\leqslant \tfrac{1}{2}R, \quad \mathcal{E}=0.9\mathcal{E}_0+0.1\mathcal{E}_0\sin(r\pi/R),\\ &\tfrac{1}{2}R\leqslant r<\tfrac{3}{2}R, \quad \mathcal{E}=\mathcal{E}_0,\\ &\tfrac{3}{2}R\leqslant r\leqslant 2R, \quad \mathcal{E}=0.9\mathcal{E}_0-0.1\mathcal{E}_0\sin(r\pi/R), \end{aligned} \tag{3}$$

where R is the bore radius. The mean life τ was approximated by an analytical form suggested by Hiskes[5]:

$$\tau=\frac{\alpha}{\mathcal{E}}\exp\left(\frac{\beta}{\mathcal{E}}\right), \tag{4}$$

where α and β were obtained by a least-squares fit to points on Hiskes' lifetime curve C in Fig. 2. The equation obtained was

$$\tau_C=\frac{1.05\times10^{-14}}{\mathcal{E}}\exp\left(\frac{49.25}{\mathcal{E}}\right). \tag{5}$$

(τ_L and τ_U are obtained from their defined relationship to τ_C, $3\tau_L=\tau_C=\frac{1}{3}\tau_U$.)

Checking of the position and shape of the observed emulsion profile (Fig. 6) required several other considerations. Due to the fringing field the beam emerged from the thin slit into the main field region (Fig. 3) with an angular displacement γ. (It should be noted that this effect prevented us from using the beam position in the emulsion to obtain an absolute value for the peak field B_0. We instead used the independently measured field values to obtain γ.)

If we designate the ion path by l, then the probability of stripping in a distance dl at l is

$$P(l)dl=\exp\left(-\int_0^l \frac{1}{\tau v}dl'\right)\frac{dl}{\tau v}.$$

We related l to the emulsion track displacement y by the small-angle approximation

$$l=2R-(4R^2+4\rho R\gamma-2\rho y)^{1/2},$$

where ρ is the radius of curvature due to the average field. Taking $\alpha=0.30\times10^{-14}$ [Eqs. (4) and (5)] and integrating over the effective slit width (0.07 cm) gave the solid-line curve of Fig. 6.

The curves in Fig. 7 show the fractional detachment as would be predicted by Hiskes. As in Fig. 2, curves U and L are considered to be the limits of uncertainty in the calculation. The curves were obtained by using the relationships of Eqs. (3) and (5) to integrate numerically the expression

$$\text{Fractional detachment}=1-\exp\left(-\int_0^{2R}\frac{1}{\tau v}dl\right).$$

The results are approximately equivalent to those for fractional detachment by a uniform field in 5×10^{-10} sec.

The main source of error in the present experiment is in the magnetic-field measurements (see Fig. 7). It is compounded from a systematic 4% in the absolute calibration with the small search coil, and a 1% random error estimated from shot-to-shot nonreproducibility of the beam timing and the magnetic field strength. The estimated error in the fractional detachment (Fig. 7) is due to uncertainty in the separation of emulsion data of the kind shown in Fig. 6 into D^0 and D^- ions.

The over-all uncertainty in the experiment is comparable with that of Hiskes' calculation; the accuracy of Khoe's result has not been estimated. Our measurements are consistent with either calculation.[21]

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[21] Preliminary results of an internal-beam cyclotron experiment at UCLA indicate breakup at equivalent electric fields smaller than Hiskes' curve L; Byron T. Wright, University of California, Los Angeles (private communication).