Observation of a Large Electric Dipole Moment Produced in Electron-Transfer Collisions of H^+ on He

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The measured intensity and polarization of Balmer-alpha radiation resulting from 40–80-keV collisions of H^+ on He exhibited a strong dependence on electric fields applied axially along the beam direction. With use of a density matrix formalism the collisionally produced electric dipole moment for the $n=3$ state was found to be large, reaching $4.4ea_0$ at the lowest collision energy. The center of the electron cloud distribution was found to lag behind the proton.

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The intensity of Balmer-alpha radiation produced in electron-transfer collisions of 40- to 80-keV protons on He shows a strong, asymmetric increase as an external axial electric field of up to 800 V/cm is applied parallel and antiparallel to the beam direction. The corresponding linear polarization fraction of the Balmer-alpha radiation exhibits an oscillatory asymmetric pattern.

The observed intensity and polarization signals were analyzed in terms of a density matrix for which the diagonal terms are equal to the electron-transfer cross sections to the $n=3$ sublevels and the real part of the off-diagonal matrix elements are directly related to the electric dipole moment of the $n=3$ state formed in the collision.

Previous experiments on coherent excitation of hydrogen in electron-atom,[1] ion-atom,[2,3] and atom-atom[4] collisions have demonstrated the possible existence of a small electric dipole moment arising from the polarization of the electron cloud along the excitation axis. However, to our knowledge no quantitative measurement of the electric dipole moment produced in a collision has ever been reported before. Our results clearly demonstrate that a large electric dipole is formed during electron-transfer collisions between 40 and 80 keV and that it increases with decreasing collision energy in the energy range considered.

The reaction studied was $H^+ + He \rightarrow H(n=3) + He^+$. A proton beam from the 200-kV Cockcroft-Walton accelerator at North Carolina State University was collimated and sent into a 5.1-cm-long target gas cell in which a uniform electric field accurate to better than 1 V/cm was applied parallel and antiparallel to the beam. A double-layer, Mumetal magnetic shield reduced residual magnetic fields to less than 1 mG. The largest residual *electric* field, due to the space charge of the ion beam, was less than 0.01 V/cm.

The pressure in the gas cell, measured with an MKS Baratron capacitance manometer, varied from 0.1 to 0.7 mTorr. The intensity of the Balmer-alpha radiation was strictly proportional to the pressure, demonstrating single-collision events. The pressure immediately before the gas cell was about 10^{-6} Torr. The diameter of the aperture in the gas cell through which the proton beam passed was 1.6 mm. The beam current ranged from 0.1 to 1.0 μA.

Balmer-alpha radiation from a 7-mm length of beam centered in the gas cell was viewed at 90° with respect to the beam. The $f/6$ optical detection system consisted of two lenses, a 6560-Å interference filter with a bandpass of 100 Å, a rotatable polaroid, and a thermoelectrically cooled EMI 9658-A photomultiplier. The optical system was adjusted to eliminate residual polarization to less than a few percent.

Tests of the intensity and polarization were made using the nearby He I line at 7280 Å over the complete range of electric fields. The systematic errors of less than 1% in the intensity and 0.01 in the polarization fraction were well below the reproducibility errors of ±5% in the intensity and ± 0.02 in the polarization fraction.

In Fig. 1 the experimental results are shown for the intensity of Balmer-alpha radiation versus electric field for 40- to 80-keV protons on helium. In general the intensity is larger for electric fields applied antiparallel to the proton beam

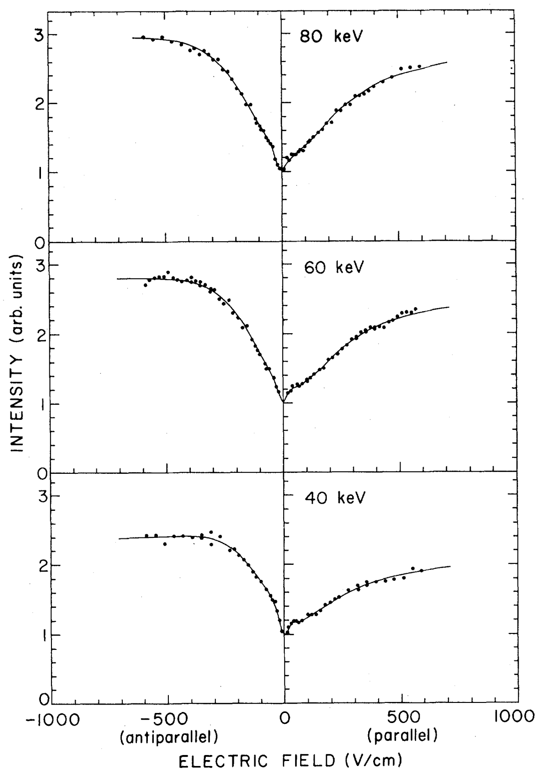

FIG. 1. The intensity of Balmer-alpha radiation vs electric field for H^+ on He. The circles are the experimental data. The solid line was calculated from Eq. (1) with elements of the density matrix chosen to obtain the best fit to experiment.

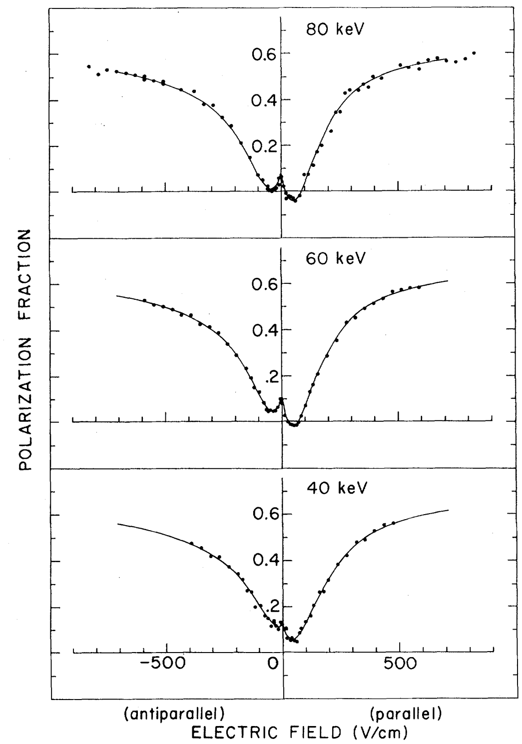

FIG. 2. The polarization fraction of Balmer-alpha radiation vs electric field for H^+ on He. The circles are experimental data; solid lines are calculated with the same density matrix parameters as in Fig. 1.

direction than parallel. The increase by a factor of 2 to 3 in the intensity with electric field is more pronounced for higher collision energies while the asymmmetry with electric field is reduced.

In Fig. 2 the experimental results are shown for the polarization fraction of the Balmer-alpha radiation versus electric field. In the region from 0 to ±100 V/cm, the polarization fraction exhibits one minimum for each electric field orientation with the lowest one occurring for electric fields parallel to the beam. The polarization fraction increases to about 0.6 in the ±800-V/cm region.

The solid curves in Figs. 1 and 2 were calculated with use of the following expression for the intensity of the emitted Balmer-alpha radiation.[5]

$$I(\vec{e}) = n_p n_{\mathrm{He}} v \vec{e}^* \cdot \overleftrightarrow{C} \cdot \vec{e}\, d\Omega, \tag{1}$$

where n_p is the number of protons passing through the scattering region per second, n_{He} is the number density of the gas atoms, v is the proton velocity, and $d\Omega$ is the solid angle subtended by the detector. The Cartesian tensor $\overleftrightarrow{C}$ is specified by its multipole moments as

$$C_{kq} = \sum_{\substack{l_1, l_2 (n=3)\\ l_0 (n=2)}} \frac{8\pi^3 e^2 \bar{\nu}^3}{4\pi\epsilon_0 \hbar c^3} (-1)^{l_1+l_2+k+1} \langle l_1 \| \vec{r} \| l_0 \rangle \langle l_0 \| \vec{r} \| l_2 \rangle \begin{Bmatrix} 1 & k & 1 \\ l_1 & l_0 & l_2 \end{Bmatrix} \bar{\rho}_{kq}(l_1 l_2), \tag{2}$$

where $\bar{\nu}$ is the average frequency of the emitted Balmer radiation, $\langle l_m \| \vec{r} \| l_n \rangle$ are reduced matrix elements for hydrogen, and $\bar{\rho}_{kq}(l_1 l_2)$ denotes multipole moments of the time-averaged density matrix $\bar{\rho}_l$ associated with the electron-transfer reaction. The time-averaged density matrix $\bar{\rho}_l$ was obtained by a projection from the j representation.

To account for formation and decay of the $n=3$ state in the $2w = 7$ mm length of our viewing region located with its midpoint at a distance d

= 25 mm from the entrance hole in the gas cell, an integration over time and space was performed:

$$\bar{\rho}_j = \int_{(d-w)/v}^{(d+w)/v} dt \int_0^t \rho_j(t')dt'. \quad (3)$$

Cascade from higher-lying states is neglected.

The time development of $\rho_j(t)$ was found from the Liouville–von Neumann equation

$$d\rho_j/dt = -(i/\hbar)[H, \rho_j] - (1/2\hbar)\{\Gamma, \rho_j\}, \quad (4)$$

where H contains the atomic Hamiltonian with electric-field-dependent terms added and decay is incorporated phenomenologically as a diagonal matrix Γ containing the decay widths of the states. The time-dependent density matrix $\rho_j(t)$ if found from

$$\rho_{\alpha\beta}(t) = \sum_{klmn} (S^{-1})_{\alpha k} S_{km}(S^{\dagger})_{nl}(S^{-1\dagger})_{l\beta} \exp[-i(\lambda_k - \lambda_l^*)t/\hbar]\rho_{mn}(0), \quad (5)$$

where the nonunitary matrix S transforms the basis states so as to diagonalize the phenomenological Hamiltonian $H - i\Gamma/2$ with eigenvalues λ_i.

A numerical program was developed to find the intensity and polarization fraction starting with an initial density matrix using the approach outlined in Eqs. (1)–(5). As a test of the numerical accuracy the results from this program agreed to within less than 0.5% of those from a similar but independently developed program at Bell Laboratories.

For our experimental arrangement the density-matrix formalism outlined above allows an almost perfect analysis of the experiment. Because the collision takes place inside the electric field region, there are no complications due to the turn-on of an electric field. Cascade contributions are small because we view hydrogen atoms only a few nanoseconds following the formation in the collision process. The limited viewing region allows a time average over several quantum beat cycles which enables us to make a precise determination of the integrated intensity. The results are relatively insensitive to the length of the gas cell and viewing region. The hydrogen atoms travel in virtually a straight line after the collision because of the small scattering angles, and the velocity of the hydrogen atoms is essentially the same as the velocity of the incoming protons.[6]

The solid curves in Figs. 1 and 2 indicate good agreement over the whole range of electric fields and suggests that our nine-parameter fitted density matrix is fairly accurate at each collision energy. The off-diagonal elements of these fitted density matrices are large which means that the phase difference between various amplitudes is only weakly dependent on the impact parameter. Furthermore, analysis shows that because of our experimental geometry the present results are not very sensitive to the imaginary part of the complex off-diagonal matrix elements. Work is in progress on determination of the imaginary part by using a transverse electric field orientation.[7]

The surprising result of this experiment is that the real parts of the odd-parity matrix elements (off-diagonal terms) are significantly different from zero, indicating that a large electric dipole is formed during the collision—in contradistinction to the Born approximation which predicts a purely imaginary odd-parity term and thus no electric dipole moment; see, for instance, Burgdörfer.[8]

The axial component of the collisionally produced electric dipole $\langle\vec{p}\rangle$ is calculated from the initial density matrix ρ_i:

$$\langle p_z\rangle = \frac{6\sqrt{6}\,\rho(s_0p_0) + 6\sqrt{3}\,[\rho(p_0d_0) + \sqrt{3}\,\rho(p_1d_1)]}{\mathrm{Tr}\rho}\, ea_0. \quad (6)$$

In Fig. 3 we show the average electric dipole moment at $t = 0$ along the direction of the ion beam as a function of collision energy. It is large, reaching a value of $4.4ea_0$ for the lowest

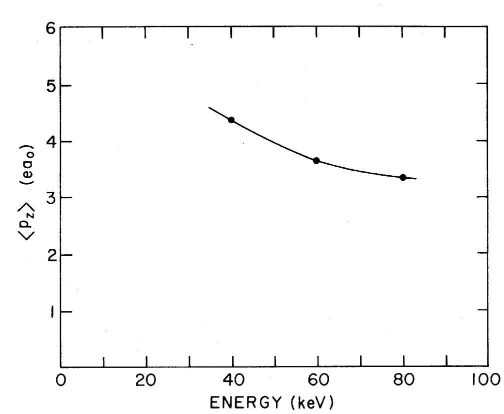

FIG. 3. Average electric dipole moment of the $n = 3$ state of the hydrogen atom formed immediately after an electron transfer collision of H^+ on He.

collision energy studied. The largest possible value the electric dipole can have in the $n=3$ manifold is $7.35ea_0$. The direction of the electric dipole is such that the electron cloud lags behind the proton immediately after the collision takes place.

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New Type of Collective Accelerator

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Described here is a collective accelerator based on magnetically confined plasma rings. Typical rings which have been produced and which have 10-kJ magnetic energy and 0.1 to 10 C of nuclei are predicted to be accelerated magnetically to 10 MJ or higher in acceleration lengths of 100 m. Applications are discussed of current drive in tokamak fusion reactors, fueling and heating magnetic fusion reactors, transuranic element synthesis, and, for focused rings, a high-energy density driver for inertial confinement fusion.

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This Letter describes a new type of collective accelerator and discusses possible applications. The accelerator is based on plasma rings,[1] confined magnetically in a nearly force-free field configuration consisting of a dipolelike poloidal field with an entrapped toroidal field. The rings, which are considered to be accelerated magnetically, have very high magnetic moment per unit of mass (~10^8 greater than superconducting pellets) and, on the other hand, may have a coulomb or more of total ion charge—greatly in excess of previous electrostatic, collective accelerators. We would like to note here that related proposals have been made to accelerate large quantities of plasma confined by the toroidal stabilized pinch,[2] and the fields of electron[3] and ion[4,5] rings.

Considering rings which have been produced experimentally, we anticipate acceleration over reasonable lengths up to kinetic energies in the 10-MJ range, and for low ion mass rings up to 1- to 10-MeV kinetic energy per nucleon. Among possible applications we discuss here are current drive, fueling, and heating of a conventional tokamak or other fusion reactor, transuranic element synthesis, and, for focused rings, a high-energy, density driver for inertial confinement systems.

Magnetically confined plasma rings have been studied for some time as possible controlled thermonuclear fusion devices. Ring formation was first demonstrated at low energy by Alfvén, Lindberg, and Mitlid in the 1950's.[1] More recently, plasma gun experiments,[6,7] shown in Fig. 1, have produced rings having typically 10-kJ magnetic energy, 10 to 20 cm major radius, 10^{19} to 10^{20} total number of ions, and a 10-eV plasma having a ratio of plasma pressure to magnetic energy density $\beta=p/(B^2/2\mu_0)$ of order 0.01. Two important aspects for the considerations here are that the lifetime of the rings is adequately long for acceleration, typically 100 μs or so, and that the rings are highly resilient, undergoing large departures from symmetry with only