point to the need for new approaches to the problem of Coulomb excitation of atoms with approximations that realistically and comprehensively incorporate, *ab initio*, the finite charge of physical projectiles.

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[7]When $\eta \ll 1$, S_{2K} rises steeply with η, approximately proportional to $\eta^4\theta^{-3}$. In the range $\eta = 5\times10^{-3}$ to $\eta = 10$, $f(\eta, \theta)$ is known numerically [G. S. Khandelwal, B. H. Choi, and E. Merzbacher, At. Data 1, 103 (1969)]. Near $\eta = 1$, S_{2K} goes through a maximum of order unity and diminishes slowly as $\eta^{-1}\ln\eta$ when $\eta \gg 1$.

[8]It is interesting to note that the signs in Eq. (3) would be reversed if the incoming projectiles were of negative charge.

[9]Testing a conjecture by Lewis, Natowitz, and Watson (Ref. 5), we measured the relative $K\alpha/K\beta$ x-ray yields in Ni and found them to be constant to ±5% for all the projectiles in the particle energy range studied. By comparison, the measured Ni x-ray yield ratios vary over a factor 2 in this range. We take this as evidence that on the scale of the effect under investigation the fluorescence yield is independent of Z_1, at least for small Z_1, as indeed one should expect on theoretical grounds.

Final States in the Dissociative Excitation of Molecular Hydrogen*

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The dissociative excitation $H_2 + e \rightarrow H(2s) + H + e$ has been studied with a time-of-flight method. Measurements of the excitation function and the angular distribution of the metastable atoms show that the slow atoms arise from dissociation out of $e\,^3\Sigma_u^+$ and $B'\,^1\Sigma_u^+$ states and from predissociation out of the $d\,^3\Pi_u^+$ and $D\,^1\Pi_u^+$ states. The fast atoms arise from a previously unreported $^1\Pi_u$ state that corresponds to a separated-atom limit in which both atoms are in $n = 2$ states.

The dissociative excitation of molecular hydrogen can proceed via the process $H_2 + e \rightarrow H(2s) + H + e$ in which one of the product hydrogen atoms is in the metastable $2^2S_{1/2}$ state. Leventhal, Robiscoe, and Lea[1] used a time-of-flight (TOF) method to measure the energy distribution of the $H(2s)$ atoms and found that the dissociative excitation yielded metastable atoms in two distinct kinetic-energy ranges: ~0.3 eV ("slow") and ~4.7 eV ("fast"). Subsequent TOF experiments on the dissociation of H_2 have been reported by Clampitt and Newton[2] and also by Czarnik and Fairchild.[3] In the present Letter we report results obtained from a TOF experiment[4] that differs from the earlier work mainly in that the detector can view the angular distribution of the $H(2s)$ atoms with a resolution of 1 degree over a range of 60 to 120 degrees with respect to the electron beam. From measurements of the excitation function and the angular distribution of both the slow and fast metastable atoms we deduce the symmetry, multiplicity, and asymptotic energy of the final states of the dissociation process; our conclusions here differ in several significant aspects from those reported by the abovementioned workers. For example, we find that the fast $H(2s)$ atoms arise from a previously unreported $^1\Pi_u$ state that corresponds to a separated-atom limit in which both H atoms are in $n = 2$ levels.

Figure 1(a) shows a schematic of the dissociative excitation process. An electron collides with the H_2 molecule and excites it "vertically" in the Franck-Condon region. If the transition is to a point above the asymptotic limit of the excited state, (or if, as in predissociation, a normally bound final state mixes with another state that has a lower asymptotic energy) then the molecule dissociates. The excess of the excitation energy over the asymptotic energy of the final state is shared, equally, as kinetic energy by the outgoing hydrogen atoms. The

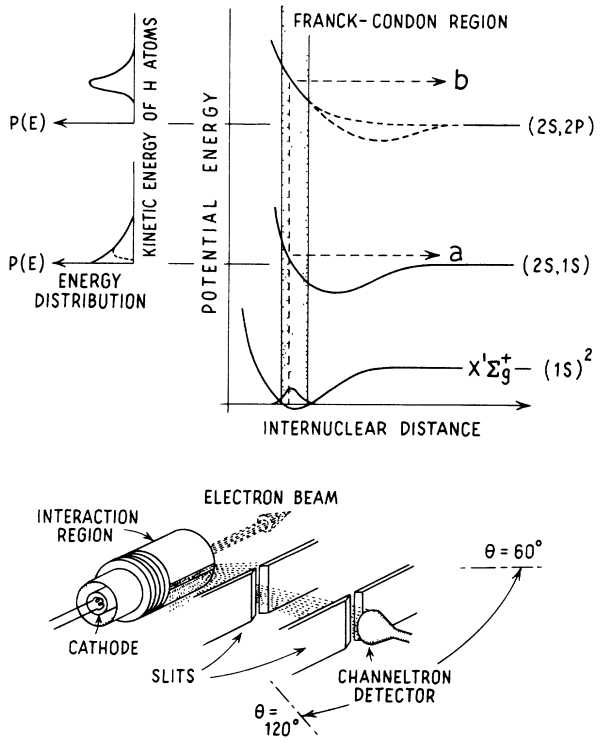

FIG. 1. (a) Schematic of dissociative excitation process leading to "fast" and "slow" metastable H(2*s*) atoms. (b) Schematic of experimental arrangement. H(2*s*) atoms impinging on the Channeltron continuous electron multiplier produce pulses which are processed and stored using a time-to-amplitude converter and multichannel analyzer.

slow H(2*s*) atoms arise both directly from transitions of type *a* and also through predissociation. The fast H(2*s*) atoms arise from transitions of type *b* in which the Franck-Condon region intersects the excited-state potential-energy curve well above the energy of the asymptotic limit.

Dunn[5] has shown that electron impact on a $^1\Sigma_g^+$ molecule can lead to Σ_g^+, Π_u, and Δ_g excited states if the molecule is perpendicular to the symmetry axis, and that the impact can lead to Σ_g^+ and Σ_u^+ excited states if the molecule is parallel to the symmetry axis. At threshold, the outgoing electrons have an *s*-wave distribution so the direction of the incoming electron beam serves as the axis of symmetry. Since the dissociation occurs in a time that is short compared to the period for molecular rotation, the trajectories of the outgoing H atoms indicate, to good approximation,[6] the molecule's orientation at the time of dissociation. Thus the angular distribution of the H(2*s*) atoms may help to determine the Λ value and the symmetry of the state that has been excited by electron impact.

Figure 1(b) shows a schematic of the experiment.[4] A beam of electrons passes along the axis of the 1.3-cm-long by 1.3-cm-diam cylindrical interaction region. The electron gun is calibrated against the known excitation functions for the metastable states of helium and argon; the electron energy resolution is ± 0.3 eV. Pulses that are 0.4 μsec or more wide are employed at a rate of 5×10^3 per second when taking TOF data. The H_2 gas passes from a storage cylinder through a needle valve and a long length of narrow-bore tubing, and the gas strikes a baffle as it enters the interaction region; thus the target H_2 molecules have a random, thermal (~400°K) motion. The pressure of H_2 in the interaction region ranges from 0.1 to 3×10^{-3} Torr for the experiments reported here. 13 cm away from the interaction region the metastable atoms are detected by allowing them to strike the cathode of a windowless electron multiplier. The pulses from the multiplier are processed and stored with a time-to-amplitude converter and a multichannel analyzer. The H(2*s*) atoms can be distinguished from metastable H_2 molecules since the atoms quench in a dc electric field that can be applied just ahead of the detector.

Slow H(2*s*) *atoms.*—Slow atoms with kinetic energies of 0.16 eV are produced only if the energy of the bombarding electrons exceeds 14.9 eV. The asymptotic limit of the final-state potential, 14.6 ± 0.3 eV, is obtained by subtracting the total kinetic energy of the final state (2×0.16 eV) from the 14.9-eV threshold. This is quite close to the sum of the 4.5-eV dissociation energy of the molecule and the 10.2-eV potential energy of the metastable atom in the H(1*s*)+H(2*s*) separated-atom limit.

The results of the previous workers[1,2] disagree concerning the relative abundance of very slow H(2*s*) atoms in the TOF distributions. In the present experiment, the distributions taken with 38-eV electron energy (where contributions from metastable H_2 molecules are still evident) and with 80-eV electron energy show a deficiency of the slowest H(2*s*) atoms in general agreement with the findings of Leventhal, Robiscoe, and Lea.[1]

The excitation function for producing slow H(2*s*) atoms (Fig. 2) can be considered as a sum of two excitation functions, one (curve α) with a rapid rise and fall as is characteristic of a singlet-triplet transition, and another (curve β)

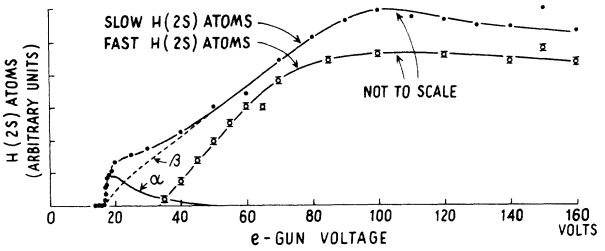

FIG. 2. Excitation functions for producing "fast" and "slow" H(2s) atoms. The slow excitation function can be decomposed into curves α and β which are characteristic of singlet-triplet– and singlet-singlet–type transitions, respectively. The fast excitation function is also characteristic of a singlet-singlet–type transition. Curve α is Khare's calculated cross section for excitation to the $a\,^3\Sigma_g^+$ state (threshold displaced to fit data).

slowly rising as is characteristic of a singlet-singlet transition.[7] Thus it appears that transitions to triplet states dominate near threshold, and that transitions to singlet states dominate at higher electron energies.

The slow H(2s) atoms produced by electrons near threshold energy appear to have an angular distribution that would be isotropic except for the kinematic momentum-transfer effects of the electron-molecule collision.[8] The excitation has no apparent dependence on the orientation of the molecule with respect to the electron beam. According to Dunn's rules,[5] this could occur if the final states were Σ_g^+, but the Franck-Condon overlap of states that seem otherwise suitable (for example $E\,^1\Sigma_g^+$ or $a\,^3\Sigma_g^+$) is quite small. However Dunn's rules also suggest that the isotropic distribution of atoms could result if the electrons excited both Σ_u^+ and Π_u final states; roughly speaking the Σ_u^+-state dissociation leads to a $\cos^2\theta$ distribution of H atoms, and the Π_u-state dissociation leads to a $\sin^2\theta$ distribution. Among the Σ_u^+ and Π_u states, one finds that the states $B'\,^1\Sigma_u^+$ and $e\,^3\Sigma_u^+$ have sizable Franck-Condon factors and that they lead directly to H(2s)+H(1s) separated-atom configurations. The states $D\,^1\Pi_u^+$ and $d\,^3\Pi_u^+$ also have appreciable Franck-Condon factors, and the D state is known[9,10] to predissociate readily to the $B'\,^1\Sigma_u^+$ state; the $d\,^3\Pi_u^+$ state is expected to predissociate readily to the $e\,^3\Sigma_u^+$ state since both states have the same united-atom limit and since the selection rules for an inhomogeneous mixing perturbation are satisfied.

We conclude from the shape of the excitation function and from the observed angular distribution that electrons with energies near 15 eV are most likely to produce slow H(2s) atoms by excitation of the molecule both to the $e\,^3\Sigma_u^+$ (dissociates) and to the $d\,^3\Pi_u^+$ (predissociates) triplet states. As the electron energy goes above threshold, excitations to the singlet $B'\,^1\Sigma_u^+$ (dissociates) and $D\,^1\Pi_u^+$ (predissociates) states become more important; for example we judge that about $\frac{2}{3}$ of the dissociative excitations leading to slow H(2s) atoms that are produced by 30-eV electrons do so by exciting these singlet states. We note that the results of Mentall and Gentieu[10] and of Czarnik and Fairchild[3] indicate that it is the transitions to the $D\,^1\Pi_u^+$ state that predominate at higher electron energies.

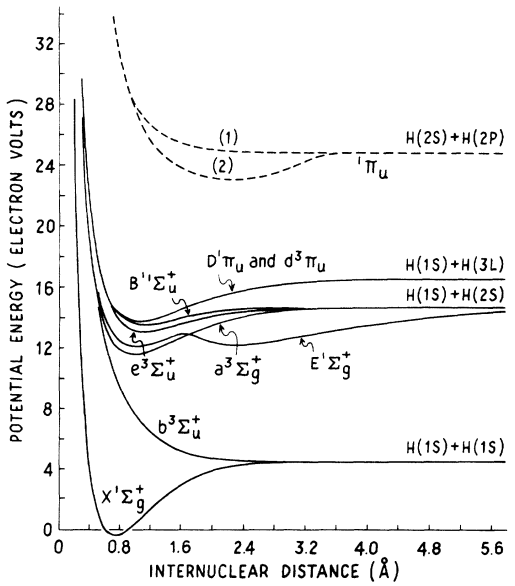

FIG. 3. Potential-energy diagram of H_2 after Sharp (see Ref. 12) showing several excited states. The approximate location of the $^1\Pi_u$ state discussed in the text has been added near the top of the figure. Whether this state is purely repulsive (1) or bound (2) cannot be determined from the data.

Fast H(2s) *atoms.*—The fast atoms that have ~3.8 eV of kinetic energy are produced only if the electron energy is more than 32 eV. The asymptotic limit of 24.4 eV is obtained by subtracting 2×3.8 eV from the 32-eV threshold; this is the same, to within experimental error, as the 24.9-eV energy that would be expected if both separated atoms were in $n=2$ states.

The excitation function for the fast H(2s) atoms (Fig. 2) shows the gradual rise characteristic of a singlet-singlet transition. The angular distribution[11] of the fast atoms suggests[5] that the final state could be either Π_u or Δ_g, but the Δ_g

is ruled out because the lowest asymptotic energy for a doubly-excited Δ_g state is 26.8 eV. This means that the final state leading to the fast atoms is a $^1\Pi_u$ state that dissociates to H(2*s*) + H(2*p*). It is noteworthy that this state (shown in Fig. 3) has not been previously reported in the literature.

The main disagreement between our conclusions and those given in the pioneering paper of Leventhal, Robiscoe, and Lea[1] is in the assignment of the excited state that is responsible for the fast H(2*s*) atoms. We differ from Czarnik and Fairchild in concluding that triplet states and pure dissociation, in addition to singlet states and predissociation, are important in the production of slow H(2*s*) atoms.

We are grateful to Professor R. T. Robiscoe for initiating the research and for his many contributions to the early stages of the experiment. We are indebted to Bryce Babcock for help in the design and construction of the apparatus. We thank John Pearl, T. E. Sharp, and Robert Freund for useful discussions.

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Enhanced Transport in Toroidal Plasma Devices due to Magnetic Perturbations*

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It is shown that a magnetic perturbation may lead to an enhanced transport of heat and particles. The observation of anomalous electron heat conduction and particle diffusion in the experimental devices may be explained by the effect.

The presence of trapped particles enhances the collisional diffusion rate in an axisymmetric toroidal plasma (banana diffusion).[1] Some of the experimental results have shown that the diffusion rate, especially for electrons, may be larger than the theoretical predictions. In the following it will be shown that magnetic perturbations may lead to an additional transport of particles and heat. The magnetic perturbations could be produced either by the unavoidable imperfections of construction or by magnetohydrodynamic turbulence.

First we consider the static perturbation. If the flux surface is not closed, there is a trivial plasma loss through the flow along the flux lines. This type of loss has been discussed previously by several authors.[2] It is assumed here that the imperfection is small and the flux surfaces are deformed but still closed.

The magnetic disturbance will modify particle orbits. We use the magnetic moment μ and the longitudinal invariant J to describe the orbits of the guiding center:

$$\mu = \tfrac{1}{2} m v_\perp^2 / B, \tag{1}$$

$$J = \oint (m v^2 - 2\mu B)^{1/2} \, dl, \tag{2}$$

where m is the mass of the particles, v and $v_\perp$ are the velocity and its perpendicular component, B is the magnetic field strength, and dl is the line element of a flux line.

The deviation of the guiding center due to the field errors is dependent on μ. The particles with large magnetic moments tend to follow curves of equal magnetic field strength and the

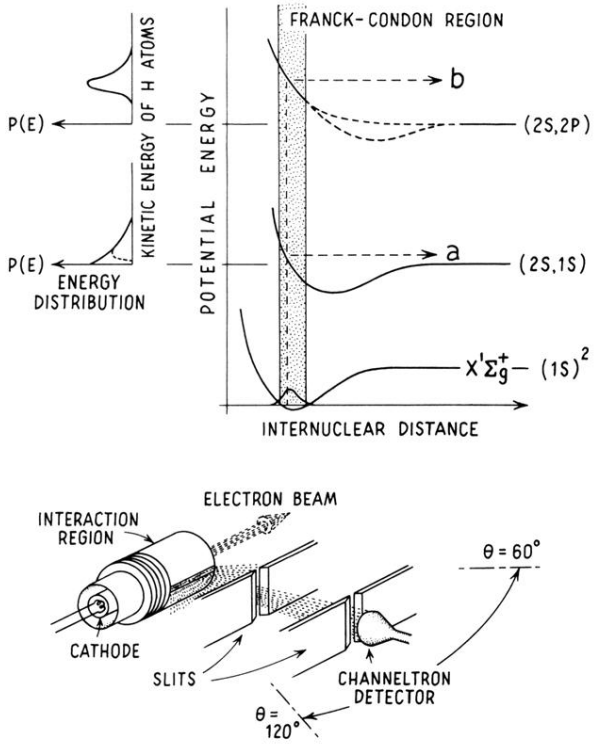

FIG. 1. (a) Schematic of dissociative excitation process leading to "fast" and "slow" metastable H(2*s*) atoms. (b) Schematic of experimental arrangement. H(2*s*) atoms impinging on the Channeltron continuous electron multiplier produce pulses which are processed and stored using a time-to-amplitude converter and multichannel analyzer.