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# ELECTRON CAPTURE TO THE CONTINUUM FROM ATOMIC HYDROGEN

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## ABSTRACT

The first known measurement of the differential cross section for electron capture to the continuum(ECC) from atomic hydrogen is presented. A 12 MeV beam of $C^{6+}$ ions traversed a static target of atomic hydrogen produced by an electron impact heated dissociation oven. The resulting ECC spectrum was obtained with a channel electron multiplier detector mounted at the exit of a 160° spherical sector electrostatic spectrometer with an angular acceptance of 2°. The ECC spectrum clearly shows the asymmetry generally associated with ECC spectra from gaseous targets. The ratio of the singly differential cross section of H to that of $H_2$ was found to be 0.80.

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## INTRODUCTION

Electron capture to the continuum (ECC) has been described, first classically by Thomas[1] in 1927, and subsequently by many authors[2-6] quantum mechanically, as a process in which a high speed bare ion projectile captures an electron from a static target atom. The electron final state is considered to be a projectile centered continuum state, i.e., the electron has essentially zero kinetic energy relative to the projectile ion after the interaction. The electron velocity distribution is peaked for $\bar{v}_{electron} \sim \bar{v}_{projectile}$ and assumes a cusp shape which is notably enhanced for $|\bar{v}_{electron}| < |\bar{v}_{projectile}|$ by the Coulomb attraction between the electron and ionized target atom. All available experimental data to date has been with non-hydrogenic targets[6,7], which prevented direct comparison of experiment and theory since the most nearly tractable theoretical formulations consider hydrogenic targets. However, an ECC spectrum has now been obtained for 12 MeV $C^{6+}$ incident on atomic hydrogen inside a dissociation over heated by electron impact[8,9].

## EXPERIMENTAL PROCEDURES

THE 150 pA projectile ion beam was produced by the 6 MV EN Tandem Van de Graaff Accelerator at Oak Ridge National Laboratory. An NMR controlled magnetic analyzer coupled with a subsequent switching magnet purified the ion beam of unwanted charge states prior to entry into the experimental beamline shown in Figure 1.

ECC electrons produced by projectile ions striking collimators C1 and C2 were swept out of the beam with an electric field of ~ 750 V/cm applied between two deflection plates D, in Figure 1 while the negligibly deflected

ions continued on through the 1.5 cm long interaction region in the dissociation oven, through a 0.32 cm passage hole in the outer sector of the spectrometer and into the Faraday cup.

Figure 2 depicts the oven-spectrometer system. The ECC electrons produced by the interaction of the projectile ions with the gas inside the oven were emitted within a narrow cone in the forward direction, traveled toward the entrance of the electron spectrometer and were deflected by the radial electric field between the sectors of the spectrometer while the ion beam trajectory was negligibly affected. Electrons having an energy appropriate for the voltage on the sectors followed essentially circular paths through the spectrometer and were detected by a channel electron multiplier (CEM) while the ion charge collected in the Faraday cup was digitized and used as the "clock" for the data acquisition system. Standard multichannel scaling techniques were used to obtain the ECC energy distribution[9].

All magnetic field components in the region containing the oven and electron spectrometer could be reduced to $\lesssim$ 20 mG by appropriately setting the current in each of three pairs of field nulling coils surrounding the oven-spectrometer vacuum chamber. These coils were also employed to maximize transmission of electrons through the spectrometer in order to compensate for any error in the optical alignment of the oven-spectrometer system along the beam axis.

The spherical sector electrostatic spectrometer used to analyze the energies of ECC electrons was constructed of two copper spherical sectors of radii 4.879 cm and 6.069 cm, subtending an angle of 160° between which the ECC electrons were transmitted into the CEM detector[10]. The 160° angle subtended by the sectors allowed easier placement of the oven and CEM relative to the spectrometer and, although the 180° doubly focusing condition was not

strictly satisfied, no noticeable effect of the astigmatism was observed in the data[9]. The energy resolution and analyzer constant (sector voltage/electron energy) were experimentally determined to be 1.03% and 0.439, respectively, for an angular acceptance of 2.0°.

A capacitance manometer controlled gas flow system supplied the hydrogen gas to the dissociation oven. Typical background vacuum chamber pressures varied from $1 \times 10^{-8}$ Torr with a hot oven and no gas to $2 \times 10^{-6}$ Torr with gas in the hot oven. The number densities of H and $H_2$ inside the hot (2250K) oven were $20 \times 10^{13}/cm^3$ and $10 \times 10^{13}/cm^3$. Background spectra were obtained by flowing gas directly into the vacuum chamber at a flow rate such that the background chamber pressure was equal to the pressure when gas flowed through the hot oven into the chamber. These "background" spectra recorded ECC events resulting from interactions with the background gas. It is to be noted that ECC electrons and electrons traveling in the forward direction resulting from direct ionization of the target atom are not distinguishable, even in principle, so that subtracting a background presumably attributable to a contribution from direct ionization is arbitrary and incorrect[11,12]. ECC contributions from non-dissociated $H_2$ were subtracted from the spectrum while background originating from heating the oven were reduced by a combination of physical barriers and electrical biasing so that the signal-to-noise ratio finally realized was 1:1.

## DATA ANALYSIS

The experimental distribution $Q(E,\Omega)$ of ECC electrons with laboratory energy E, emitted within solid angle $\Omega$, has a functional form given by[9]

$$Q(E,\Omega) = \int_E \int_\Omega S(E,\Omega) \frac{d^2\sigma}{dE d\Omega} dE d\Omega, \qquad (1)$$

where $\frac{d^2\sigma}{dEd\Omega}$ is the laboratory differential cross section for ECC production and $S'(E,\Omega)$ is the transmission function of the spectrometer[9]. Expansion of the electron velocity-dependent differential cross section $\frac{d^2\sigma}{dv}$, in a power series in the electron-ion velocity difference, further expanding the coefficients of that power series in terms of Legendre polynomials, and finally transforming to an energy dependent cross section where $\frac{d^2\sigma}{dEd\Omega} = \frac{v}{m}\frac{d^2\sigma}{dv}$, allows a least squares regression to be employed to fit experimental data to the functional form in Equation (1)[9,14,18].

The oven-spectrometer system was calibrated for absolute cross sections using the data of C. R. Vane[15] for an argon gas target[9] and the energy integration limits for the ECC cross sections were ±8% of the electron laboratory energy at the peak of the cusp[7,9,15].

## RESULTS AND CONCLUSIONS

Figure 3 shows ECC spectra obtained for 12 MeV $C^{6+}$ incident on (a) $H_2$, (b) H + $H_2$ at 2250K, and (c) the resultant spectrum from atomic hydrogen. The dissociation fraction f, is noted in Figure 3(b). All spectra exhibit the asymmetry observed in ECC spectra from gaseous targets. Table 1 presents the cross sections and full width at half maxima (FWHM) in atomic units of velocity for the spectra in Figure 3. A thorough study of possible systematic errors indicated that counting statistics were restricted only by duration of data accumulation as all background spectra were essentially horizontal and flat. The deconvolution of the energy distribution yielded parameters which have been shown to be consistent with similar parameters obtained from helium ECC spectra[16] and while the cross sections are believed to be accurate within the precision of the errors noted in Table 1, the values of FWHM are listed only for general comparison. Finally, projectile

velocities well above 10 au are required to study the asymptotic behavior of the cusp shape; an energy region where, unfortunately, ECC cross sections are small and nuclear interactions contribute to background noise[4,16]. Further reduction of non-nuclear background signals with the present technology of dissociation ovens would indeed be difficult, if at all possible. Detailed studies of ECC from atomic hydrogen in the asymptotic velocity regime would therefore seem to require alternate methods of producing practical targets.

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Table 1. ECC DIFFERENTIAL CROSS SECTIONS FOR12 MeV $C^{6+}$ INCIDENT ON MOLECULAR AND ATOMIC HYDROGEN

| TARGET | $\frac{cm^2}{sr\text{-}particle}$ * | Velocity ** FWHM (au) |
|---|---|---|
| $H_2$ | $(5.52 \pm 3.4) \times 10^{-19}$ | 0.219 |
| H | $(4.48 \pm 2.3) \times 10^{-19}$ | 0.414 |

*One particle is defined as one molecule for $H_2$ and one atom for H.

**Using Dettmann's formula[6] with angular acceptance of 2° yields FWHM of 0.331 au.

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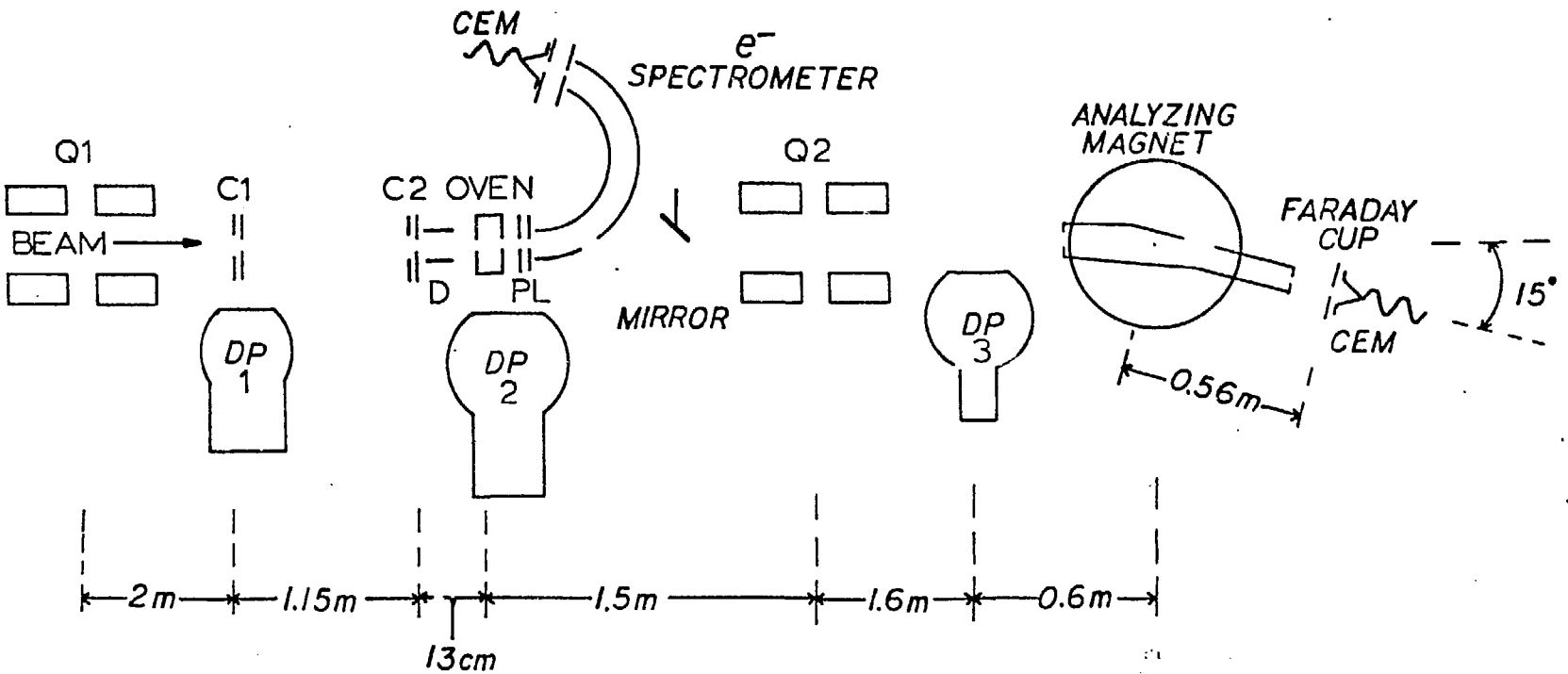
## FIGURE CAPTIONS

Figure 1 — Experimental Beam Line. Magnetic quadrupole doublets are denoted by Q and DP denotes oil diffusion pumps.

Figure 2 — Electron Analyzing Apparatus. Resistors $R_a$ and $R_b$ are used to define ground potential along circular arc of radius $\bar{r} = (a + b)/2$ where a and b are the radii of the inner and outer sectors, respectively. Photon limiters and bias on CEM cone reduced background due to hot dissociation oven.

Figure 3 — ECC Spectra for 12 MeV $C^{6+}$ Incident on (a) $H_2$, (b) H + $H_2$ at 2250K, and (c) H. Dissociation fraction f, is noted on spectrum (b). Solid lines are least squares fits to data obtained from distribution function in Equation (1). $H_2$ spectrum in (a) was normalized appropriately and subtracted from spectrum (b) to give spectrum (c).

FIGURE 1


CEM
e⁻
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Q1
C1
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Q2
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BEAM
D
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MIRROR
DP
1
DP
2
DP
3
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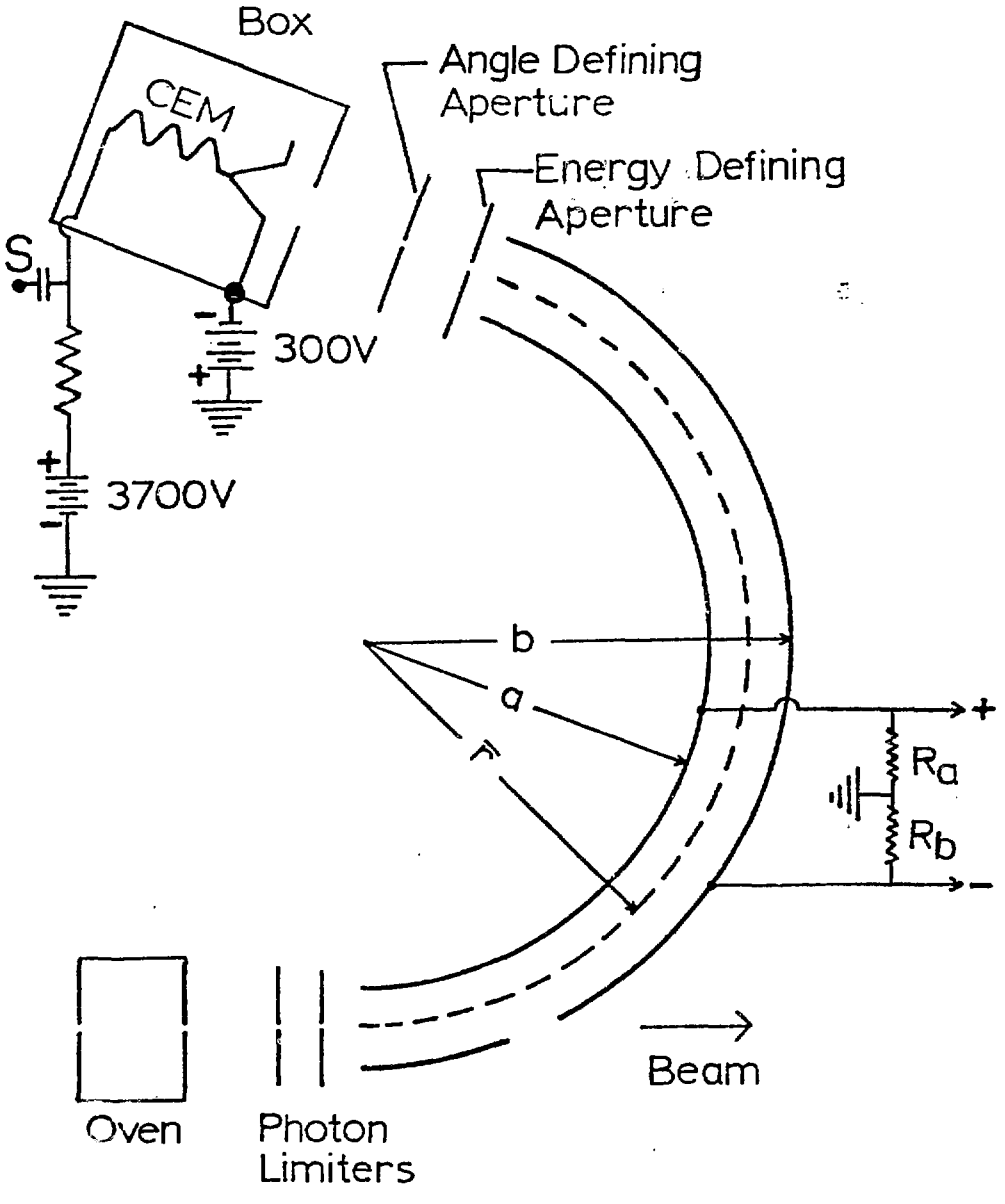
15°
0.56m
2m
1.15m
1.5m
1.6m
0.6m
13cm

FIGURE 2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CEM
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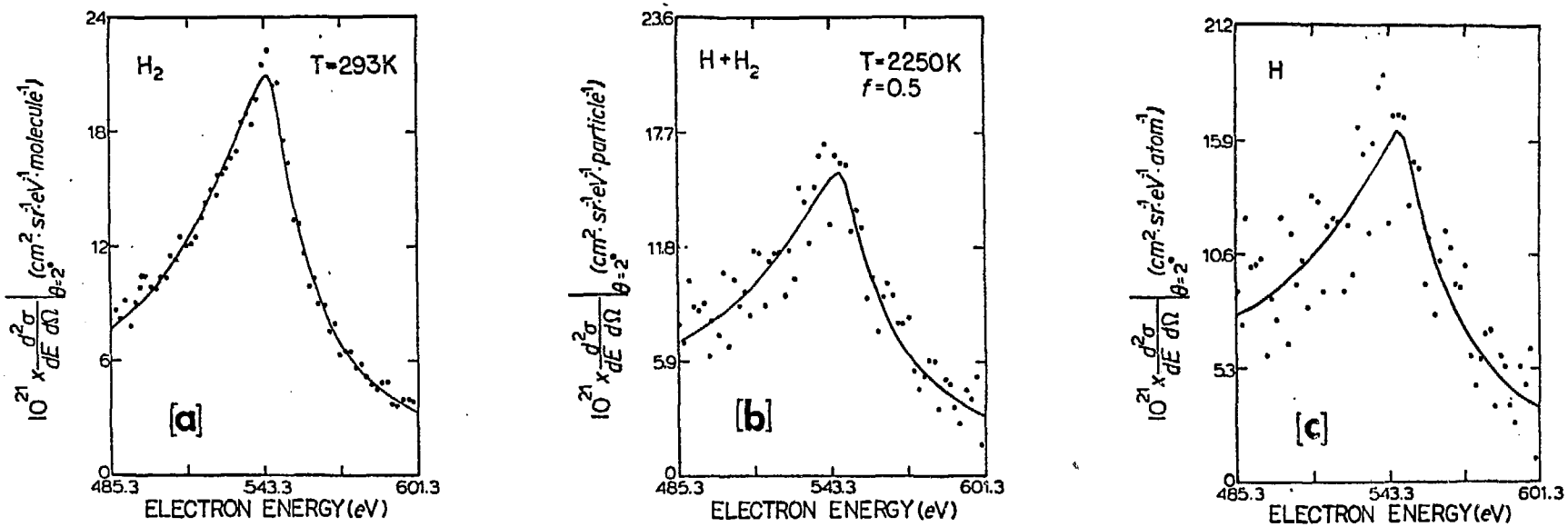
Photon
Limiters

FIGURE 3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T=293K
[a]
24
18
12
6
0
485.3
543.3
601.3
ELECTRON ENERGY(eV)
$10^{21} \times \frac{d^2\sigma}{dE\, d\Omega}\Big|_{\theta=2^\circ}$ (cm$^2$·sr$^{-1}$·eV$^{-1}$·molecule$^{-1}$)
H+H2
T=2250K
f=0.5
[b]
23.6
17.7
11.8
5.9
0
485.3
543.3
601.3
ELECTRON ENERGY(eV)
$10^{21} \times \frac{d^2\sigma}{dE\, d\Omega}\Big|_{\theta=2^\circ}$ (cm$^2$·sr$^{-1}$·eV$^{-1}$·particle$^{-1}$)
H
[c]
21.2
15.9
10.6
5.3
0
485.3
543.3
601.3
ELECTRON ENERGY(eV)
$10^{21} \times \frac{d^2\sigma}{dE\, d\Omega}\Big|_{\theta=2^\circ}$ (cm$^2$·sr$^{-1}$·eV$^{-1}$·atom$^{-1}$)