Collisional single electron loss of 0.5-MeV H^-: Energy spectrum of detached electrons coincident with the formation of H(2p)

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We have measured the energy spectrum of detached electrons at $\theta_L = 0°$ in coincidence with Lyman-α photons from the excitation and subsequent decay of H(2p) produced during the process $H^- + He \rightarrow H(2p) + e^- + He^*$ at 0.5-MeV incident ion energy. We find that this electron energy distribution mimics the so-called very sharp peak feature of the doubly differential cross section previously measured under e^--H coincidence conditions. This result shows that excitation of H is responsible for the very sharp peak and that the detached electron energy distribution associated with H(2p) is significantly different from the distribution associated with the production of H(1s).

I. INTRODUCTION

In a recent paper[1] we summarized the features of the doubly differential cross section (DDCS) in the extreme forward direction in the laboratory frame, $0° \leq \theta_L \leq 3°$, of electrons ejected during single-electron-loss (SEL) processes of H^- incident on He at 0.5 MeV. In particular, it was shown that the very sharp peak at $v_e = v_i$, where v_e and v_i are the electron and ion laboratory speeds, respectively, is due to SEL processes and not to double-electron-loss processes. Earlier work[2] had already established the fact that, in the H frame, the shape of this very sharp peak is independent of whether the target is He or Ar, is independent of the incident ion energy in the range 100–700 keV/u, and that the angular distribution of these very-low-energy electrons is isotropic. In light of these findings and on the basis of Born calculations[3,4] of the electron DDCS near $\theta_L = 0°$ for the specific SEL process

$$H^- + He \rightarrow H(1s) + e^- + He^* , \quad (1)$$

and a preliminary Born calculation[5] that accounts for excitation of the H atom to H(2s), it was conjectured in Ref. 1 that the most likely candidates responsible for this very sharp peak are SEL processes that produce excited H atoms.

Electron detachment collisions of H^- with H, H_2, and Ar are known to produce excited states of H. Excitation of H to highly excited states has been measured in the incident energy range from 2.8 to 60 keV/u for the above systems.[6] The excitation yield was found to follow a $1/n^3$ scaling for highly excited states (n between 12 and 28), whereas the yield of $n = 2$ and $n = 3$ states was found to be higher than that estimated by $1/n^3$ scaling.[6,7] Since most of the excitation resides in the lower n states it is reasonable to address our conjecture regarding the energy distribution of detached electrons associated with excitation by selecting those electrons associated (coincident) with the production of H(2p).

In this paper we report on measurements of the detached electron energy spectrum at $\theta_L = 0°$ in coincidence with Lyman-α photons from the subsequent decay of H(2p) produced during the process,

$$H^- + He \rightarrow H(2p) + e^- + He^* . \quad (2)$$

We note that the excitation of He was not specified in these measurements. The role of the mean excitation energy of the target has been theoretically established for process (1) (Ref. 8) and, in principle, can be expected to play a role in process (2). Nevertheless, the role of target excitation appears to be relatively unimportant with regard to the energy distribution of detached electrons in process (2) since the shape of the very sharp peak is independent of the target,[2] whereas the mean excitation energy depends on the target.[8]

The electron–Lyman-α-photon coincidence DDCS was found to mimic the shape of the previously measured very sharp peak thus confirming our conjecture and the notion that excitation of H in the final state must be considered in order to fully account for the energy distribution of detached electrons.[4]

II. EXPERIMENTAL PROCEDURES

Detailed discussions of the apparatus and electronics used are given in Refs. 1 and 2. Additional details pertinent to this experiment are given below.

Small slots were cut in both the inner and outer cylinders of the cylindrical mirror electron energy analyzer in order to allow the photons to leave the analyzer. These slots were centered along the line traveled by the ion beam and positioned in such a manner that the photon detector could accept photons from the outer edge of the He cross beam to within 1 cm of the inner cylinder wall, a distance of approximately 1.5 cm. At 0.5 MeV incident energy in the length of the viewed path approximately corresponds to the H(2p) decay time of 1.6 nsec. The Lyman-α-photon detector consisted of a channeltron (Galileo No. 4039) preceded by a 1-mm-thick LiF window. The overall acceptance solid angle of the photon detector was about 10^{-2} sr and had an estimated efficiency for Lyman-α-photons between 0.1% and 1%. Since the photon detector was just able to view the outer edge of the He cross beam some of the detected photons may have come from $He^+(n=4) \rightarrow He^+(n=2)$ transitions. Although photons from the He^+ transitions would be time correlated to some electrons there is no reason to expect that the energy distribution of these electrons would be the same as the very sharp peak. Moreover, the shape of the very sharp peak is known to be the same for Ar as it is for He. Hence, all detected photons were attributed to the $H(2p) \rightarrow H(1s)$ transition.

The electrons were energy analyzed under the following analyzer conditions: $\Delta E/E = 0.014$, full width at half maximum; $\Delta\theta_L = 0.85°$. Under these analyzer conditions and the conditions noted above for the photon detector the maximum electron–Lyman-α-photon coincidence count rate was about 0.01 sec^{-1} using a "clean" H^- beam (see Ref. 1) of about 4 nA with a diameter of 1.2 mm and He cross beam with a number density of about 10^{14} cm^{-3} and a 2–3-mm diameter. The electron-photon coincidence count rate was found to be negligible with the He cross beam off. The post-interaction beam was dumped into a Faraday cup and the collected charge was used to provide a normalization basis for the data.

The energy spectrum of electrons coincident with Lyman-α photons from decay $H(2p) \rightarrow H(1s)$ was obtained as follows. The analyzer voltage was set to pass electrons of a given energy which were ultimately detected by a channeltron. Pulses from the electron channeltron were suitably amplified, delayed, and used as stop signals for a time-to-amplitude converter (TAC). The photon channeltron pulses were treated in a similar manner, except for a delay, and used to start the TAC. After the accumulation of a TAC spectrum the process was repeated at another analyzer voltage. The standard coincidence circuitry was the same as that used in Ref. 1. The main difference between this coincidence experiment and our previous coincidence measurements is that the analyzer voltage was kept constant during a run instead of being swept. This procedure was dictated by the low coincidence rates which required 4–8-h runs for just one electron energy. A typical TAC spectrum is shown in Fig. 1. The electron-photon coincidence counts were determined by subtracting the average accidental counts from the time correlated peak.

III. RESULTS

The electron–Lyman-α-photon coincidence DDCS at $\theta_L = 0°$ is shown in Fig. 2. Also shown in Fig. 2 is the very sharp peak obtained previously by a subtraction process[2] but which has been averaged over the poorer energy resolution of the present work. Examples of the results of this subtraction process can be seen in Fig. 3 of Ref. 2. The very sharp peak was normalized at 272.8 eV to the average electron–Lyman-α-photon coincidence data from several runs at this energy.

One thing to note is that the electron–Lyman-α-photon spectrum does not have the low-energy peak seen in the high-resolution uncorrelated spectra. (With the resolution of this experiment the peak appears as a prominent shoulder on the low-energy side of the very sharp peak.) Inspection clearly shows that there is no suggestion of a shoulder on the electron-photon coincidence spectrum but only a single peak. Thus, it is clear that the energy distribution of detached electrons associated with SEL processes producing $H(2p)$ excitation is significantly different from SEL processes that produce $H(1s)$.

With only a single peak in evidence in the coincidence spectrum it is clear that the interference between $l=0$ and $l=1$ electron partial waves is much less pronounced than it is for process (1) where a double-peaked structure is seen. This result is in qualitative agreement with the preliminary theoretical calculation that accounts for excitation to $H(2s)$, where the effect of the interference between $l=0$ and $l=1$ was found to be greatly suppressed compared to the case where H is produced in the ground state.[5] Such a small interference effect would not be seen

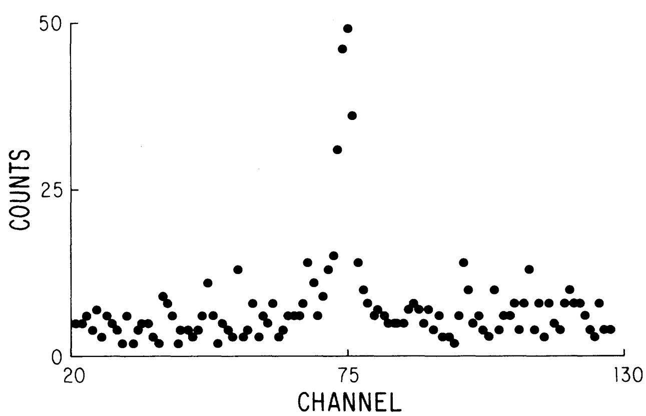

FIG. 1. A typical output spectrum of the TAC set on the 200-nsec range with the analyzer voltage set to detect electrons near the peak of the DDCS. The stop leg of the TAC had a 100-nsec delay inserted.

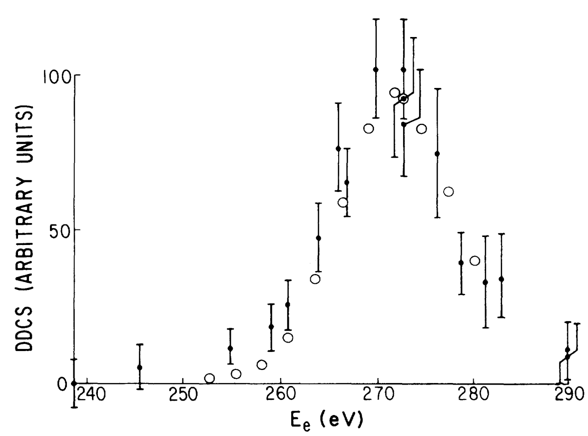

FIG. 2. Shown are the results of the electron–Lyman-α-photon coincidences as a function of electron energy measured at $\theta_L = 0°$. The open circles are the energy-averaged DDCS of the very sharp peak as discussed in the text.

in our data.

We wish to point out that in other higher-resolution data at 0.5 MeV, both with and without the e^--H coincidence requirement (see Fig. 2 of Ref. 1), there is no evidence of the excitation and subsequent decay of the $^1P^o$ shape resonance. Evidence of excitation of this resonance has been found using 100-keV H^-.[9] Although the resolution used in our work is not quite good enough to detect the resonance in competition with the direct excitation of H(2p) we note that the electron–Lyman-α-photon coincidence measurement ought to be especially sensitive to the $^1P^o$ shape resonance. For example, if H(2p) excitations were fed exclusively via the $^1P^o$ shape resonance, the electron energy distribution would be expected to show a pronounced dip[3] at $v_e = v_i$ which would be discernible at this resolution. Therefore, it seems that the excitation of the $^1P^o$ resonance channel must be quite small relative to direct H(2p) excitation above about 100 keV.

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