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Observation of electrons from the $^1P^\circ$ resonance of D^-

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We have measured the electron energy spectra near 0° produced in collisions of D^- with Ar. Using a 400-keV D^- beam and with good experimental energy and angular resolution we have found structure in the ejected electron energy spectra which is due to the decay of the $^1P^\circ$ shape resonance. The doubly differential cross sections (DDCS's) have been measured as a function of angle and it was found that this structure disappeared for laboratory angles greater than 1° as expected. A resonance contribution to the DDCS's was extracted at $\theta_L = 0°$, transformed to the projectile frame, and fit with a Breit-Wigner shape. Our resonant energy is in reasonable agreement with other experiments. We also find a small asymmetry in the two resonant structures in the laboratory measurements at $\theta_L = 0°$.

I. INTRODUCTION

The doubly excited state of D^- (H^-) with the configuration $2s2p$ which decays to both the $2s$ and $2p$ states and the $1s$ state of the neutral atom has been seen in e-H scattering,[1] photon emission from a hydrogen discharge,[2] photoionization,[3] and recently in collisions between H^- and rare gases.[4–6] The collision experiment of Anderson, Bangsgaard, and Sørensen[4] found a resonance energy of about 17 meV with a width of 21 meV in reasonable agreement with theoretical calculations of the resonance parameters. References 4, 5, and 6 find that in the projectile frame the cross section is larger for forward emission than for emission in the backward direction. The investigation reported here was initiated for three reasons: (i) to determine the angular behavior of the resonance structures, (ii) to measure the doubly differential cross sections (DDCS) with a fine energy mesh, and (iii) to show the projectile frame fit to the resonance in some detail. Thus, in the work presented here we have investigated the double differential cross sections, for electron loss of D^- in the angular range $\theta_L = 0°$ to $\theta_L = 1.33°$ and present the $\theta_L = 0°$ DDCS in the projectile frame after it has been corrected for the analyzer resolution function. The frame transformation was calculated taking into account our experimental ΔE_L and $\Delta\Omega_L$ and we found it to agree with the differential form down to projectile frame energies of about 1 meV.

II. EXPERIMENTAL ARRANGEMENT

D^- ions were extracted from a duoplasmatron ion source, accelerated, and momentum analyzed at 400 keV. The D^- beam was cleared of any other charged (or neutral) components by electrostatic deflection after it had passed through two circular apertures of diameter 0.4 and 0.5 mm and just before it entered the electron energy analyzer. After passing through another 1-mm aperture the beam intersected the gas cross beam. The analyzer is similar to that described by Meckbach.[7] Our angular acceptance, $\Delta\theta$, was 0.2° and our energy resolution was $\Delta E_L / E_L = 0.005$, full width at half maximum (FWHM). Details of the analyzer can be found elsewhere.[8]

III. RESULTS

Figure 1 shows data at small angles near $\theta_L = 0°$. These spectra (uncorrected for the analyzer resolution function) show the rapid disappearance of the resonance structure and demonstrate the need for good angular resolution in order to observe the resonance well. The disappearance of the resonance structures is, of course, a kinematic effect; for example, a 20-meV electron in the D^- frame is not found at laboratory angles greater than 0.8°.

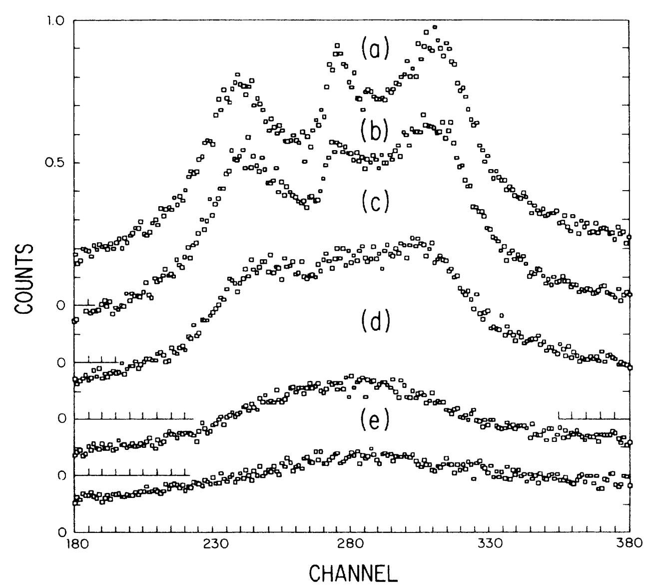

FIG. 1. Spectra in the laboratory frame at (a) 0°, (b) 0.33°, (c) 0.67°, (d) 1.0°, (e) 1.33°. These are uncorrected raw data.

In order to display data in the projectile frame the transformation from the laboratory frame to the projectile frame must be made,

$$\left[\frac{d^2\sigma}{dE\,d\Omega}\right]_P=\left[\frac{d^2\sigma}{dE\,d\Omega}\right]_L\frac{(\Delta E\Delta\Omega)_L}{(\Delta E\Delta\Omega)_P}\ .$$

In the infinitesimal limit the ratio on the right is given by $v_P/v_e\equiv(E_p/E_L)^{1/2}$, where E_p and v_P are the projectile energy and velocity, respectively, associated with the nominal laboratory energy, E_L. We calculated the ratio $(\Delta E\Delta\Omega)_L/(\Delta E\Delta\Omega)_P$ for our finite resolutions as a function of energy in the projectile frame and found that this direct calculation agrees well with the velocity ratio down to energies of about 1 meV. Since, in our data, the effects of the resonance begin to appear at about 1 meV we used the simpler velocity ratio to transform our data.

Figure 2 shows our data for $v_e>v_i$ (e is electron, i is ion) taken at $\theta_L=0°$ and transformed into the projectile frame. This is forward ejection in the projectile frame. The resonance is clearly visible as are contributions from other processes. Reference 4 extracted the resonant contribution by assuming a "nonresonant" (NR) contribution of the form $\sigma_{\rm NR}=a+bv_P$ and a total cross section of the form $\sigma_{\rm tot}=\sigma_{\rm NR}+\sigma_{\rm res}$. We were unable to do this. Our measured cross section becomes essentially constant for energies greater than 80 meV. Although not shown, this trend continues up to 250 meV. Since our data could not be fit by the above $\sigma_{\rm NR}$ we resorted to a somewhat arbitrary procedure to estimate the nonresonant contribution. The procedure we used was to draw a smooth curve from channel 285 to channel 350 for the forward emission and from channel 265 to 200 for the backward emission. (The $v_e=v_i$ peak was in channel 275.) This was done as is indicated by the dashed lines in Fig. 3 which is the $\theta_L=0°$ data corrected for the analyzer resolution function. The results of transforming these smooth nonresonant contributions to the projectile frame are also shown in Fig. 2.

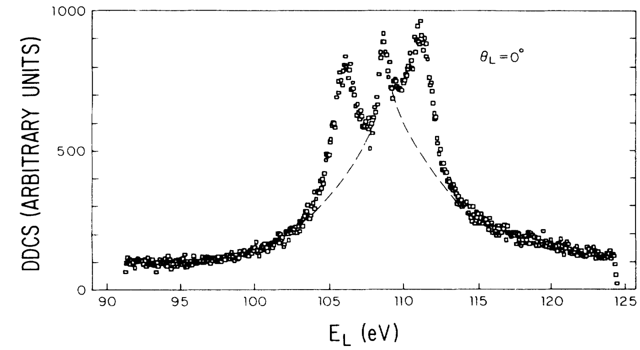

FIG. 3. Corrected laboratory DDCS at $\theta_L=0°$. Besides the data, the smooth nonresonant contributions to the cross section are indicated by the dashed lines.

Figure 4 shows the results of this procedure. Both $\theta_p=0°$ and $\theta_p=180°$ data are shown. However, only half the available points are plotted to keep the figure from being overcrowded. Also shown is a fit to the data. Separate fits to the $\theta_p=0°$ and $\theta_p=180°$ data gave similar results. Therefore, all data points were used in the final fit. The resonance can decay to either the $n=1$ or the $n=2$ states of H. For the decay to $n=1$, the width Γ_1 is taken to be constant across the resonance since the electron energy is about 10 eV. The energy dependence of the resonance width for the decay to the $n=2$ states (which produce the low-energy electrons) cannot be ig-

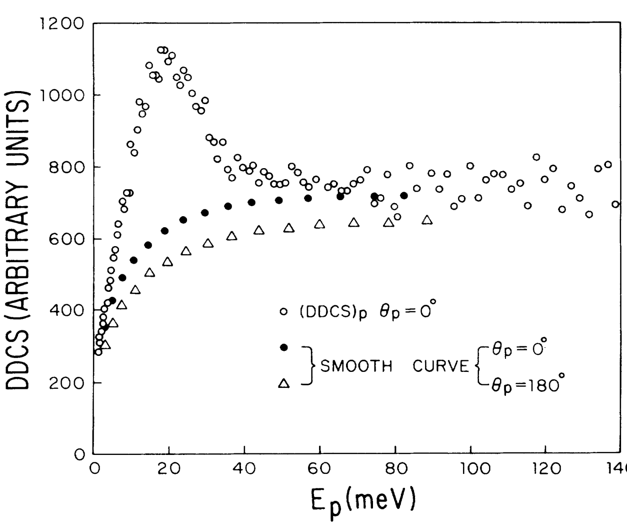

FIG. 2. DDCS for $\theta_p=0°$ transformed to the projectile frame. Also shown are the smooth nonresonant contributions to the DDCS at both $\theta_p=0°$ and $\theta_p=180°$ as discussed in the text.

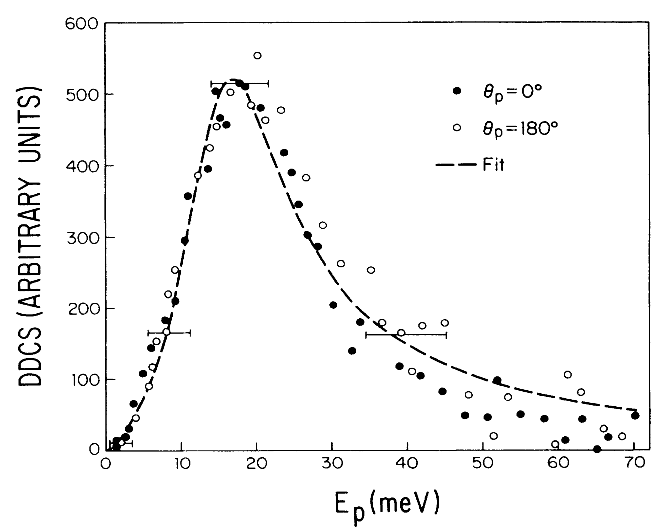

FIG. 4. Resonant contributions at $\theta_p=0°$ and $\theta_p=180°$. The dashed line is the fit to the data discussed in the text. The horizontal bars are the ΔE_p for four different values of E_p which were calculated from the known laboratory resolutions. ΔE_p is the range of projectile frame energies which contribute at the nominal value E_p.

nored and is given by $\Gamma_2 = \gamma E_p^{3/2}$.[9] The fitting function was, therefore,

$$\sigma_R \approx \left[\frac{\Gamma_2}{(E_p - E_0)^2 + (\Gamma_1 + \Gamma_2)^2/4} \right] .$$

The three parameters Γ_1, γ, and E_0 were determined by a search routine adapted from Bevington.[10] The values obtained were $E_0 = 21.4$ meV, $\Gamma_1 = 1.4$ meV, and $\gamma = 0.34$ $\text{meV}^{-1/2}$. Near the resonance $\Gamma_1 \ll \Gamma_2$ as expected.[9]

Even though our nonresonant curves seem to show a slight asymmetry, when one takes the total projectile frame data available at all laboratory angles, no real asymmetry is apparent. Taking the average of data at 20, 25, 30, and 35 meV (where the resonance is most evident) at each laboratory angle, 0°, 0.33°, 0.67°, and 1°, the resulting angular distribution in the projectile frame was found to be isotropic to within $\pm 10\%$. The angles ranged from $\theta_p = 0° - 60°$ and $120° - 180°$.

Since we completed this work, it has come to our attention that any procedure, such as the one used here, which attempts to extract a resonant contribution to these electron-loss processes may be inappropriate. Liu and Starace[11] have completed a five-channel calculation of 0.5-MeV H^- collisions with He and find resonant structures similar to those shown here. However, they find that the coherent sum of the various amplitudes predicts that the peak with $v_e < v_i$ is due primarily to decay to H 2p while the peak with $v_e > v_i$ is due primarily to the decay to H 2s. Further experimental investigation of these predictions would require measurement of coincidences between electrons and Ly-α photons.

Note added in proof. Since this manuscript was completed the calculation referred to above has been redone. It was found that the decay to the 2p and 2s states both contribute to the peaks at $v_e > v_i$ and $v_e < v_i$. However, the decay to the 2s state gives a substantially larger contribution to the peak at $v_e > v_i$ than to the other.

ACKNOWLEDGMENT

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