The ultimate limit on cooling is determined by a competition of the damping rate on the vibrational energy due to laser cooling and the "noise" excitation of the vibrational energy due to the random occurrence (in time) of the photon impulses. In the limit where $\nu_v \ll \Delta\nu$ and when one tunes for maximum cooling ($\nu_L - \nu_0 = -\frac{1}{2}\Delta\nu$), the resulting kinetic energy is approximately equal to $h\Delta\nu/8$ corresponding to $T \simeq 0.5\times10^{-3}$ K for the transitions discussed here. One can use the scattered photons from the cooling process as a monitor in a double-resonance experiment. Since the laser is not needed for trapping, it can be turned off for a relatively long time while the resonance of interest is probed. The possiblity also exists to use a mixture of ions—one kind which can be laser cooled and by collisions cools the other kind which are the ions of spectroscopic interest. We note that the cooling method is quite general and can in principle be applied to other cases such as ions or nuclei bound in solid lattice.

The authors wish to acknowledge the help of the other members of the Time and Frequency Division, in particular the support and leadership of H. Hellwig, and electronics construction by C. Klepper. The basic trap structure was built by one of the authors (D.J.W.) and R. S. VanDyck, Jr., at the University of Washington and was used with the kind permission of H. G. Dehmelt. The cooling limit was estimated with key input from E. M. Purcell and D. J. Larson, Harvard University. This work was funded in part by the U. S. Office of Naval Research under Contract No. N00014-77-F-0046.

[1]T. W. Hänsch and A. L. Schawlow, Opt. Commun. 13, 68 (1975).
[2]D. J. Wineland and H. Dehmelt, Bull. Am. Phys. Soc. 20, 637 (1975).
[3]A. Ashkin, Phys. Rev. Lett. 24, 156 (1970), and 25, 1321 (1970), and 40, 729 (1978).
[4]V. S. Letokhov, Comments At. Mol. Phys. 6, 119 (1977), and many earlier references contained herein.
[5]H. G. Dehmelt and F. L. Walls, Phys. Rev. Lett. 21, 127 (1968); H. Dehmelt, in *Advances in Atomic and Molecular Physics*, edited by D. R. Bates and I. Esterman (Academic, New York, 1967, 1969), Vols. 3 and 5; D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).
[6]R. A. Heppner, F. L. Walls, W. T. Armstrong, and G. H. Dunn, Phys. Rev. A 13, 1000 (1976).
[7]D. A. Church and H. G. Dehmelt, J. Appl. Phys. 40, 3421 (1969).
[8]R. S. VanDyck, Jr., P. B. Schwinberg, and H. G. Dehmelt, in Proceedings of Orbis Scientiae, Coral Gables, 1978 (Plenum, New York, to be published).
[9]J. Byrne and P. S. Farago, Proc. Phys. Soc. (London) 86, 801 (1965).
[10]W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, U. S. National Bureau of Standards, National Standards Reference Data Series —22 (U. S. GPO, Washington, D. C., 1969), Vol. II.
[11]S. Bashkin and J. O. Stoner, Jr., *Atomic Energy Levels and Grotrian Diagrams* (North-Holland, Amsterdam, 1975).

Collisional Electron Detachment of H^-: A Complete Angular Distribution

M. G. Menendez and M. M. Duncan
Department of Physics and Astronomy, University of Georgia, Athens, Georgia 30602
(Received 17 April 1978)

The doubly differential cross section resulting from electron loss of 0.5-MeV H^- ions in collisions with Ar were measured from 0° to 173°. The singly differential cross section (SDCS), angular distribution, for the $v_e \approx v_i$ group was integrated over solid angle and normalized to the known total electron-loss cross section. This SDCS was found to be dissimilar to that predicted by an electron scattering model previously used to describe projectile ionization. However, the SDCS was found to resemble, with some notable differences, the elastic scattering of electrons from Ar.

Experimental information on spectral shapes and angular dependences are necessary for an understanding of the details of electron detachment processes. In a recent paper[1] secondary-electron energy spectra, the doubly differential cross section (DDCS), resulting from electron loss of fast H^- ions were measured in the angular range 0°–15°. The ion energy was 0.5 MeV and the target was Ar. As expected, in the laboratory frame, the DDCS for projectile ionization exhibit-

ed peaks near $E_e = \frac{1}{2} m_e v_e^2 = \frac{1}{2} m_e v_i^2$, where v_i is the laboratory ion velocity and v_e is the laboratory electron velocity. However, in the extreme forward direction, 0°–3°, evidence was found for two groups of electrons each having a distinct angular dependence. Although one group was peaked at an energy slightly less than E_e, both groups were associated with projectile ionization.

During a collision, H^- may suffer either single electron loss (SEL) or double electron loss (DEL). In Ref. 1, the two groups seen near 0° were tentatively identified as belonging to the two different processes. The experimental DDCS were integrated above background as described elsewhere[2] and the resulting singly differential cross sections (SDCS) were integrated over the limited angular range of these measurements. However, the ratio of the yield of the presumed SEL electrons to the yield of the presumed DEL electrons was in serious disagreement with measured ratios of total cross sections.[3] It was suggested that, since most of the DEL electrons had not been accounted for in the forward direction, measurements of the DDCS over the entire angular range were needed if identification of the two electron groups was to be at all meaningful. It was hoped that any unexpected features of these spectra might shed some light on the energy and angular distribution of a two-electron–loss process.

In this paper, we present the first essentially complete measurement of the angular distribution of the secondary electrons ejected during the collisional ionization of any projectile. These results will be discussed in the light of a simple electron-scattering model[4] (ESM) and a recent optical-model calculation of electron scattering from Ar.[5]

Details of the scattering chamber, cross-beam characteristics, background identification, and overall experimental procedures have previously been described.[2] The results presented here in the angular range 0°–20° were taken with an experimental arrangement similar to that used in Ref. 1. In order to make measurements at large angles the following modifications were made: (a) The analyzer entrance apertures were changed from 0.5 mm diam to 2.0 mm diam, and the analyzer was moved from a position 80 mm to one 180 mm from the center of the chamber; and (b) the electron suppressor was removed from its position approximately 2 cm in front of the gas assembly and was incorporated into a shortened beam collimator at the entrance to the chamber. The expected effects of these modifications were the following: (i) They decreased slightly both the energy and angular resolution. Comparison of data taken with both sets of apertures indicated that these effects were insufficient to affect the shapes of the peaks. (ii) They led to a less precise definition of the incident beam. This effect did not produce any undesirable effects for detection angles greater than 5°. With the electron suppressor at the chamber entrance, electrons produced via collisions of H^- with background gas between the collimator and the cross beam could subsequently scatter from the cross beam. However, the number of electrons so produced was estimated to be only about 1% of the number of electrons produced by the ionization of H^- in traversing the cross beam. Furthermore, since the total detachment cross section and the electron scattering cross section are about the same magnitude, the subsequent scattering of these "background" produced electrons was expected to produce an immeasurably small contribution to the electron yield in the back hemisphere. This expectation was verified experimentally. Thus the modified system was used between 5° and 173° and the original system was used from 0° to 20°. The two sets of data were then normalized to each other by using data in the common angular interval of 5°–20°. The data were taken for a fixed number of monitor counts and runs for a given experimental configuration were normalized on that basis.

Figure 1 shows the relative shapes of the DDCS at three angles (5°, 90°, and 173°) without regard to their relative heights. At 5° the electron group appeared symmetric about an energy somewhat less than that for $v_e = v_i$. Previous calculations based on the ESM produced relatively symmetric peaks but were centered at $v_e = v_i$. The two small bumps marked by the letter A on the wings of the distribution were identified as resulting from the $(2s^2)^1S$ autoionizing state of H^-. At 90° the spectrum was no longer symmetric and the maximum had moved to an energy nearer to but still less than that corresponding to $v_e = v_i$. At this angle, where the SDCS was near its minimum, the yield of the $v_e \approx v_i$ electrons had decreased to such an extent that the smooth background, primarily due to continuum electrons from target ionization and above which this group always appears, was clearly visible and was rising at low energies as expected. Also, the Ar Auger electrons found near 200 eV were apparent and are marked by the letter B. Although the energy resolution of these experiments was insuffi-

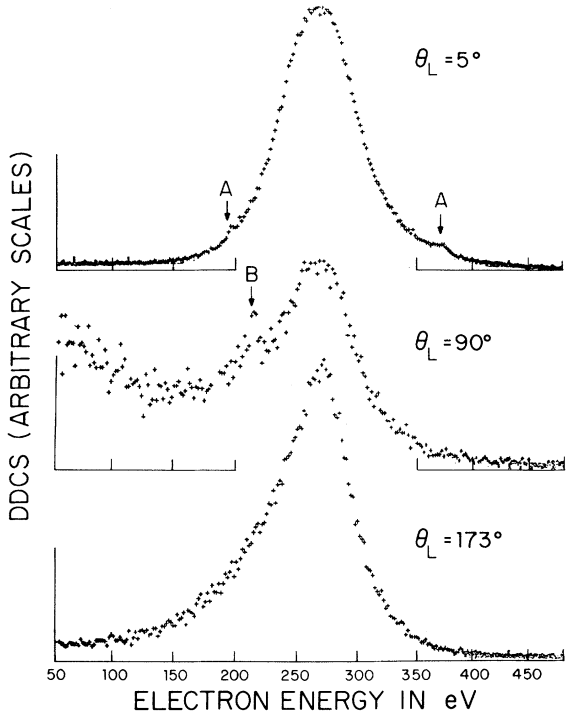

FIG. 1. Secondary-electron energy spectra at 5°, 90°, and 173° from H^--Ar collisions at 0.5 MeV. See text for explanations of the symbols A and B.

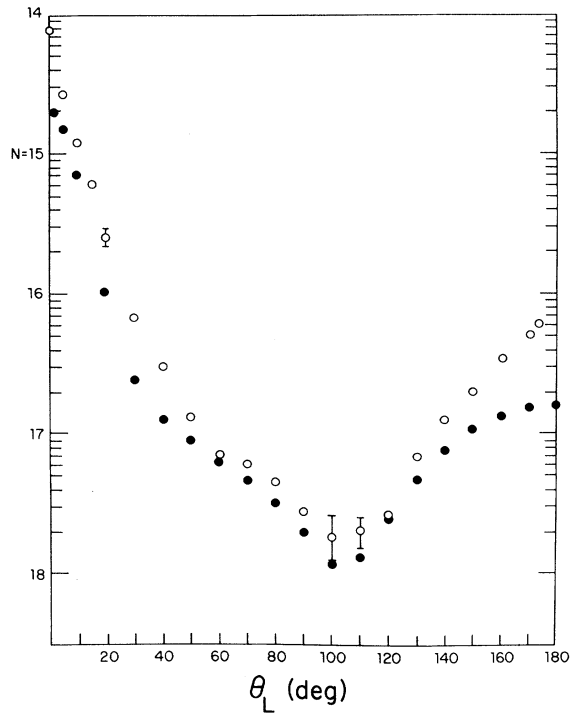

FIG. 2. A comparison of the angular distribution of the $v_e \approx v_i$ group as measured in this experiment (open circles) and calculated for elastic electron-Ar scattering at 270 eV (closed circles).

cient to resolve the structure of these transitions, a single peak did appear at 208 eV. Consideration of previously measured Auger spectra[6] from 300-keV proton bombardment of Ar enabled us to estimate that the dominant transitions would appear as a single peak near 207 eV. Thus, our energy calibration, which was previously made using a tungsten filament, was confirmed. Since these Auger electrons contributed such a small fraction of the total yield, no effort was made to subtract them from the total yield above background. At 173° the yield increased significantly over the minimum and continued to show a prominent low-energy tail which was first seen at about 30°. The energy at the maximum of the 173° spectrum was approximately the same as found at 90°.

Integration of the DDCS above background provided the data for an angular distribution. This relative SDCS was then integrated over the solid angle from $\theta = 0°$ to $\theta = 180°$, after extrapolating the data from 173° to 180°. Under the reasonable assumption that most of the electrons lost by H^- appear in the $v_e \approx v_i$ group, the value of this integral was equated to the known total electron detachment cross section of H^- from 0.5-MeV collisions with Ar.[3] Thus a conversion to absolute cross sections was obtained. These data are presented in Fig. 2. The estimated uncertainties in the data are 20% or less unless larger error bars are shown. (The error bars shown at 20° are ± 20%.) Most of the data points are the result of averaging two or more experimental runs and although much more data were available, in the interest of clarity, only a few points were chosen near 0°.

The dominant process in H^- collisions with Ar is SEL and thus the spectra were expected to exhibit, in the main, the features of this process. Unfortunately, no specific calculation of SEL was available to compare with the experimental data. However, it was hoped that the Born calculation of projectile ionization of Drepper and Briggs[7] would provide a guide for understanding the measured angular distribution at large angles. These workers argue that when the electron is ejected at large angles it is possible to neglect the "bare" Coulomb interaction of the projectile and show that for this condition the calculation reduces to the ESM. The ESM treats the target as a struc-

tureless object defined by a screened Coulomb potential and the projectile electrons are given an appropriate velocity distribution but are otherwise treated as free. Since there is no bare Coulomb interaction in the final state for the SEL process, it seemed reasonable to compare the data with ESM calculations. The SDCS predicted by the ESM, and thus the Born calculation as well, decreased monotonically with increasing angle. This is in sharp disagreement with the results shown in Fig. 2. One is forced, therefore, to conclude that any model which treats the target as a screened potential and the electron as free is not a suitable description of SEL at large angles. (Note that this discussion excludes angles near 0° where the spectra are known to be complex.)

Nevertheless, H^- is a weakly bound system and it does not seem unreasonable to expect that during SEL the H^- electrons may interact with the target as essentially free electrons. However, rather than treating this free electron as scattering from a screened potential it was possible to compare the data with a more realistic description of the electron scattering process. A recent optical-model calculation for the electron elastic-scattering cross section from Ar was available.[5] This calculation took into account the internal structure of Ar, approximated exchange effects between the incident electron and target electrons and, most importantly, was in excellent agreement with e-Ar elastic-scattering data.[8] In Fig. 2 the optical-model calculation for 270-eV electrons[9] is shown and exhibits a rather good overall agreement with the measured angular distribution. It was found that the calculated distribution remained essentially unchanged when the incident electron was given a velocity distribution appropriate to its initial state. The general qualitative agreement between the e-Ar scattering calculations and the data presented here, together with the fact that the ESM provided such a poor representation of the data, suggested—not unexpectedly—that details of the target are important in the collisional detachment of H^-.

A close comparison of the data and the calculation, however, reveals differences that may be significant. The experimental results are always greater than the e-Ar elastic-scattering cross section but the deviations are largest near 0° and 180°. The large difference near 0° was not unexpected, since there is evidence for DEL as well as SEL in this angular region. The difference between the optical-model calculations and the experimental results in the backward direction may be a manifestation of the fact that the electron is, in fact, bound and therefore does not participate in the collision as a free electron. For example, in the rest frame of the H^- ion the Ar atom approaches with a velocity v_i. If a nearly head-on collision occurs between the Ar nucleus and one of the H^- electrons, the struck electron would recoil with a velocity near $2v_i$ in the backward direction. In the laboratory frame, this electron would then contribute to the $v_e \approx v_i$ group near 180°. However, even if this presumed physical process is effective in causing the SDCS to rise in the backward direction, it is not possible to distinguish between SEL and DEL since the final state of the other H^- electron is unknown.

In summary, the details of the variations of the DDCS with angle were observed. Spectral shapes and peak energies were found to depend on the angle of ejection of the electron. Neither of these effects had been predicted. The ESM was found to disagree with experiment, suggesting that the target structure is an important aspect of the collisional detachment of H^-. Although the e-Ar scattering data were found to be in qualitative agreement with experiment, notable differences cast doubt on the validity of describing the electron as free. Furthermore, it is very likely that effects due to both target and projectile structure were seen, thus supporting the notion that the details of the dynamics of the atomic interactions are important even for weakly bound systems. Experiments using other two-electron projectiles are currently under way.

[1]M. M. Duncan and M. G. Menendez, Phys. Rev. A 16, 1799 (1977).

[2]M. G. Menendez, M. M. Duncan, F. L. Eisile, and B. R. Junker, Phys. Rev. A 15, 80 (1977).

[3]J. Heinemeier, P. Hvelplund, and F. R. Simpson, J. Phys. B 9, 2699 (1976).

[4]D. Burch, H. Wieman, and W. B. Ingalls, Phys. Rev. Lett. 30, 1823 (1973).

[5]I. E. McCarthy, C. J. Noble, B. A. Phillips, and A. D. Turnbull, Phys. Rev. A 15, 2173 (1977).

[6]D. J. Volz and M. E. Rudd, Phys. Rev. A 2, 1395 (1970); D. J. Volz, Ph.D. dissertation, University of Nebraska, 1968 (unpublished).

[7]F. Drepper and J. S. Briggs, J. Phys. B 9, 2063 (1976).

[8]J. F. Williams and B. A. Willis, J. Phys. B 8, 1670 (1975); R. H. J. Jansen, F. J. deHeer, H. J. Luyken, B. van Wingerden, and H. J. Blaauw, J. Phys. B 9, 185 (1976).

[9]Kindly supplied to us by Dr. McCarthy.