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by

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Abstract

The angular distribution of neutral hydrogen following electron detachment from H^- has been measured for H^- on nitrogen and hydrogen gas, both for neutral atoms left in the 2S state, and for all neutrals independent of the state of excitation. The results are essentially in agreement with calculations based on the Born approximation, although there is some disagreement in detail.

I. Introduction

The distribution in angle of neutral hydrogen following single collision electron detachment from H^- should be well described by the Born approximation for incident energies in the MeV region, where the speed of the ion is greater than that of the atomic electrons. Angular distributions of the center of mass of the hydrogen atom and detached electron have been calculated by Gillespie¹ and by Lee and Chen.² More recently Genoni and Wright³ and Franz, Wright and Genoni⁴ have emphasized that the motion of the stripped atom differs significantly from that of the center of mass and that the width of the distribution of atoms left in excited states is considerably broader than that of atoms left in the ground state.

Here we report measurements of the angular distribution of neutral hydrogen following stripping of H^- on nitrogen and hydrogen gas. We present results both for atoms left in the 2S excited state and for neutral atoms independent of their state of excitation.

The apparatus used in these measurements will be described in Section II of this report, followed by a presentation of the experimental results and a simple analysis in Section III. We present our conclusions in Section IV.

II. Apparatus

a. Overall Considerations

The angular deflection of a hydrogen atom after collisional detachment of one electron from H^- was estimated in the Born approximation¹⁻⁴ to be of the order of 10 microradians for hydrogen left in the ground state. In consequence, the H^- beam must be collimated to a few microradians, at least in one dimension. If the experiment is to be confined to a few meters overall length, a position-sensitive detector with precision of a few μm is needed. In addition, if excited-state atoms are to be detected unambiguously, techniques are needed to tag these atoms. A schematic view of the apparatus we have developed for this measurement is shown in Fig. 1. The H^- beam from the vertical Van de Graaff accelerator at the Los Alamos Ion Beam Facility passes through defining slits, where it is shaped to roughly 2 mm high by 1/2 mm wide. After

Fig. 1. Plan view of the experimental apparatus; scale is maintained in the beam direction.

this, two sets of precision-machined slits collimate the beam to a few microradians divergence in the horizontal plane. The collimated beam passes through a windowless gas cell where some of the ions are stripped of their extra electron, then into a region containing an electric field of about 1 kV/cm. There atoms left in the 2S state acquire 2P state amplitude through the Stark effect and quickly decay to the ground state. The resulting Lyman-alpha photon can be detected by special photomultiplier tubes viewing the quench region. The hydrogen atoms next traverse the region between the deflector plates, in which a strong vertical electric field separates the unstripped and doubly stripped components of the beam from the neutral component. The charged components are counted to monitor the relative beam intensity. Finally, the neutral atoms pass through a third set of slits and into a plastic scintillator where they are counted.. The slits are mounted on a translation stage capable of moving in one- μm steps. By

stepping the final slit in front of the scintillator, the distribution in position, and hence in angle, of the neutral beam is measured. A coincidence with a photon indicates that the neutral atom was in the 2S state following stripping. The separate components of this apparatus will be described in greater detail below.

b. Beam Collimation

Techniques for collimating beams to high precision have been developed for the construction of nuclear microprobes, both for negative⁵ and positive⁶ beams. The group at Heidelberg⁶ emphasized careful slit design and fabrication to minimize the number of scattered atoms left in the beam after passing through the slits. They demonstrated the feasibility of collimating a beam to an angular spread of a few microradians with an apparatus a few meters long. The advantage of working with negative ions was demonstrated at Los Alamos, where Armstrong and Wegner⁵ pointed out that the components of the beam that had hit the slit edges would be stripped with high probability and therefore could be separated from the transmitted portion by electrostatic or magnetic deflection of the unstripped beam. It is our further observation that the part of the beam that passes through the edges of the slits is spread over a rather broad angular range by multiple scattering, so that little of this is mixed with the transmitted beam. We have taken advantage of all of these considerations in the design of our collimator.

The slits themselves are indicated schematically in Fig. 2. Since most of the particles hitting the slit scatter into forward angles, it is desirable that the slit

face be nearly parallel to the beam direction, Fig. 2. Diagram of micro-collimating slits. The slit opening is approximately two microns.

so that the beam penetrates only a narrow region of the slit edge. Our slits were made with a 3° angle. The edges of the slit should be as clean and smooth as possible. The slits were fabricated in the Los Alamos micromachining shop, where flat surfaces with machining marks smaller than $0.03 \mu\text{m}$ are readily achieved. Blanks were first machined from copper, then gold was electroplated onto the copper. The two surfaces forming the slit edge were then machined flat, with the tool moving into the edge. The slits were then examined with a scanning electron microscope (SEM) for quality. Some roughness was present on the edges, but in most cases it was well below one μm in size. In practice, these slits worked very well.

The slits were mounted against a flat surface, and the slit width was adjusted with screw driven wedges. The slit opening was measured with the SEM since at a few μm the width of the diffraction pattern with ordinary light is too broad to permit straightforward use of optical techniques. The second

collimating slit and the analyzing slit widths were set at about two μm . The first collimating slit was found to close when set at two μm and exposed to the beam. When the opening was set at five μm , it closed down to around two μm , producing a satisfactory beam.

The slits were mounted on a three-meter-long optical table⁷ for vibration suppression. The only coupling of the table to the other parts of the apparatus, such as the vacuum system, was through flexible bellows. Mechanical vibration proved to be no problem in the experiment, so further mechanical isolation was not necessary.

The collimating slits were mounted on precision translation stages⁸ identical to those used for the analyzing slit so that they could be moved for alignment. In addition to the microslit, each stage contained a 130- μm slit and a circular hole 6.35 mm in diameter. The slits were first positioned approximately by optically aligning the mounts. Next, the beam was brought through the 6-mm holes, and then the coarse slits were translated to the beam position. Finally the precision slits were brought into position, using the final scintillator to detect the beam.

c. The Stripper

The stripper cell is a cylinder 150 mm long and about 50 mm in diameter through which gas can be flowed. The beam enters and leaves the cell through slits 0.4 mm wide by 2.3 mm high. The box in which the stripper is mounted is pumped by a 2400-

liter/second diffusion pump, and baffles in the beamline inhibit the migration of gas from this region into other parts of the apparatus. The pressure in the stripper is measured by a baratron gauge mounted outside the chamber. It proved necessary to mount the stripper cell on the optical table to preserve alignment when the system was evacuated.

The stripper had to be shielded from magnetic fields; a simple calculation shows that, in a field of 0.5 Gauss perpendicular to the beamline, an ion stripped at the front of the 150-mm-long cell deflects 30 microradians less than one stripped at the back of the cell. Consequently, a high-permeability magnetic shield was placed around the stripper. The field inside this shield, at the entrance and exit of the stripper, was below 0.01 Gauss.

d. The 2S Detector

The 2S component of the beam was identified by a coincidence between a Lyman-alpha photon and a proton in the last scintillator. The photons were detected in UV-sensitive phototubes obtained commercially⁹. Coincidence rates of one count per second were achieved at the peak of the distribution.

e. The Beam Monitor

The charged particle beams coming out of the stripper were split in an electric field produced by a parallel plate deflector immediately following the quench plates. The plates are 50-cm long, with a 2-cm separation. Applied fields of

~ 4 kV were sufficient to deflect the charged beams into plastic scintillators mounted about 0.6 cm above and below the center of the beamline. The sum of the counts in these counters proved to be a reliable monitor of the beam current.

f. The Position-Sensitive Detector System

The angular measurements were done by using a precision translation stage to move a fine slit in front of a particle detector. A proton energy spectrum, measured with good resolution, established that the microcollimated beam contained only a negligibly small energy degraded component, and that very good energy resolution was not needed in the final detector. Consequently, a plastic scintillator like the monitor detectors was used to detect the neutral atoms.

The stage was positioned by a stepper motor under control of a microcomputer. The position was read by an optical encoder and was recorded as the stage was stepped. The stage moved reliably in one- μm steps.

III. Data and Analysis

Figure 3 shows the horizontal profile of the microcollimated beam as analyzed by the position detector. The shape is approximately Gaussian and 8 μm wide at half maximum. Since the distance from the second

Fig. 3. Position scan of the collimated beam. The dashed curve is a Monte Carlo simulation, with 2.5 and 2 μm slit widths.

collimating slit is 2.2 meters, the angular width is about 4 microradians. This was typical of the beam quality we achieved. The dashed curve is the result of a Monte Carlo simulation of the slit system. It is sensitive to the widths of the slits; the dashed curve shown was calculated with the width of the front set at $2.5\text{ }\mu\text{m}$ and the two others set at $2\text{ }\mu\text{m}$.

In Fig. 4a we show the horizontal profile of a neutral hydrogen beam produced by stripping of H^- on nitrogen at about 20 millitorr. The width of the curve is about $30\text{ }\mu\text{m}$ FWHM, much larger than the width of the beam from Fig. 3. Figure 4b shows the distribution of neutrals measured with the gas supply to the stripper closed. Because of the bending of the H^- beam by the magnetic field of the Earth, the position of the neutral peaks

Fig. 4a. Singles rate for neutral hydrogen as a function of slit position. The stripping gas was N_2 at a pressure of 20 millitorr. The solid curve connects the data points. Fig. 4b. The singles rate with the gas feed closed. The vertical scale is about 40 times smaller than in Fig. 4a.

depends on where the stripping took place; the peaks in Fig. 4b are produced by collisions within various parts of the beamline. Subsequent tuning of the beam eliminated all but a small peak coincident with the peak of Fig. 4a; the small peak was probably produced by collisions with residual gas in the stripper cell.

Figure 5 shows the singles data from stripping on nitrogen with a Lorentzian curve fit to it. (The distance scale has been divided by 1.54 meters, the separation of the slit and center of the stripper, to give the angle of deflection

Fig. 5. Singles data for nitrogen stripper at 20 millitorr. The curve is a Lorentzian fit to the data with 18.4 microradians FWHM.

in μrad .) The fit is clearly very good and suggests that a Lorentzian provides a useful characterization of the data. For the singles data, the FWHM is about 18 microradians.

Similar singles data for stripping on hydrogen gas are shown in Fig. 6. In Fig. 6a the hydrogen pressure was 12.8 millitorr; the width of the best-fit Lorentzian is 19.6 microradians. Figure 6b shows data and a fit at 25.4 millitorr. The width of the Lorentzian curve is

18.7 microradians. It probably is not significant that the width for the higher gas pressure is slightly smaller; this probably indicates that the sensitivity of the fitting procedure is limited. We note, however, that the widths are essentially the same as those for the nitrogen data.

Fig. 6a. Singles data for hydrogen stripper at 12.8 millitorr. The curve is a Lorentzian fit with 19.6 microradians FWHM.

Fig. 6b. Singles data for hydrogen stripper at 25.4 millitorr. The curve is a Lorentzian fit with 18.7 microradians FWHM

Figure 7 shows the angular distribution of neutrals in coincidence with Lyman-alpha photons in the quench region. The stripping gas was nitrogen at 20 millitorr pressure. The shape is approximately the same as that of the singles data but roughly 2.5 times wider. The solid curve is a Lorentzian curve of 50 microradians FWHM. As for the singles data, the quality of the fit indicates that one can usefully parameterize the data by a Lorentzian width.

The data presented here are an average over scattering angle. The height of the slits is very large in comparison to the width of the distributions of the stripped atoms in both the

ground and excited states. Consequently the measured intensity at any slit position is proportional to the differential cross section summed over the range of polar scattering angles passed by the slit.

The result is a broadening of the measured distribution compared to what one would obtain with

collimation in two dimensions

and a distortion of its shape. The distribution before averaging is not Lorentzian.

In Fig. 8 we compare the calculations of Wright and Genoni³ to the coincidence data. Their calculations used uncorrelated bound-state wave functions and plane outgoing waves; the theoretical curves have been integrated over slit

height and normalized to unity at the peak. The data are normalized the same way. The fit is reasonably good in the

Fig. 7. The 2S coincidence rate as a function of angle. The target gas was nitrogen at 20 millitorr pressure. The vertical bars indicate the statistical uncertainties. The solid curve is a Lorentzian fit with 50 microradians FWHM.

Fig. 8. The averaged Born approximation curve compared to the coincidence data. Both curves are normalized to unity at the maximum.

central region but deviates significantly from the data in the wings of the distribution.

The singles data contain contributions from all neutral species produced in the stripper. The curves in Fig. 9 are weighted averages of the integrated ground state and 2S calcu-

lations of Wright and Genoni. The points are the singles data of Fig. 4. If we assume that the distribution

for hydrogen left in the 2S state is representative of all excited-state distributions, this permits us to estimate the fraction of hydrogen left in excited states by the stripping process. The center solid curve, with 25% of the stripped hydrogen in the excited states, represents the data very well. The other curves are for 15% and 35% excited-state fractions.

IV. Discussion

Based on the comparison of our data with the theory, the stripping of several MeV H^- by gas molecules seems to be reasonably well understood. The angular width of the 2S component, if not the full distribution, is reasonably well

Fig. 9. The singles data fitted by a mixture of ground state and excited state distributions. The solid curve has a 25% excited state mixture. The dots represent the data. The dashed and dash-dot lines have 35% and 15% excited state, respectively.

accounted for by calculations using the Born approximation. The measured singles angular distribution is also well fit by the calculations if about 25% of the observed neutral atoms are assumed to be left in excited states by the stripping process. The width of the excited state component is ~2.5 times greater than that of the ground state component of the stripped beam, as expected, and the effect of the choice of stripping gas on the widths of the angular distributions appears to be very small.

More work remains to be done. We should repeat these measurements at higher and lower energies to confirm that the widths scale as the square root of the beam energy, as predicted by the Born approximation. Measurements with a d-beam at one energy would be useful to test theoretical expectations. Measurements of the populations of specific final states, especially the 2S, as a function of stripper thickness are important, and might be done with the existing apparatus.

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