METASTABLE HYDROGEN ATOMS PRODUCED IN CHARGE EXCHANGE*

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Since the experiments by Lamb and Retherford on a beam of hydrogen atoms in the metastable $2s$ state, the traditional source of metastable hydrogen atoms has been some slight modification of the one used in those historic experiments. It consists of an oven to dissociate molecular hydrogen and an electron gun to excite to the $2s$ state the ground-state atoms thus formed. A source of $H(2s)$ with improved intensity and collimation will make possible numerous new experiments and improvements on old experiments. It was with the idea of finding a better way of producing metastable hydrogen atom beams that the experiment reported here was undertaken.

In 1959, Madansky and Owen[1] proposed a source of polarized protons using metastable hydrogen atoms, and proposed use of a charge-exchange reaction between protons and molecular hydrogen to produce the metastable hydrogen atoms. They detected metastable hydrogen atoms produced when 10-keV protons passed through molecular hydrogen. Colli et al.[2] have found a peak cross section for this process of 5×10^{-17} cm^2 for a proton energy of about 25 keV. The cross section decreases rapidly at proton energies below 25 keV. Alexeff[3] was unsuccessful in detecting $H(2s)$ produced in this process with protons in the energy range 150-600 eV.

For most experiments on metastable hydrogen atoms, it is desirable to have these atoms at lower velocity than is possible when producing them by a collision between protons and H_2. This is particularly true when the metastable hydrogen atoms must be separated from the beam of protons by electric or magnetic fields, because if the protons are too fast the fields required to deflect the protons will quench too many of the metastable atoms.

Several trends in data on cross sections for charge-exchange reactions suggest that molecular hydrogen is not a good donor gas for converting protons to $H(2s)$ by charge exchange if the object is to have a high cross section at low proton energy. (1) In a charge-exchange process of the type $A^+ + B \rightarrow A + B^+$, the velocity of A^+ at which the maximum cross section occurs is proportional to the energy defect ΔE.[4] The energy defect is the difference between the internal energies of the initial and final states for infinite separation. (2) The maximum cross section for charge exchange is large when the energy defect is small.[5] (3) The maximum cross section is large when the ionization energy of the atoms is small.[5]

Therefore, a better choice for the atom from which the proton could gain an electron is cesium for the following reasons: (1) The energy defect for the process $H^+ + Cs \rightarrow H(2s) + Cs^+$ is only 0.49 eV in contrast to 12 eV for the process $H^+ + H_2 \rightarrow H(2s) + H_2^+$, and (2) the ionization energy of cesium is only 3.89 eV in contrast to 15.44 eV for H_2. Both of these facts lead one to expect a high cross section at low proton energy for the reaction $H^+ + Cs \rightarrow H(2s) + Cs^+$. To verify this prediction we have measured the cross section for this reaction over the proton energy range of 160 eV to 3000 eV.

A diagram of the apparatus used is shown in Fig. 1. Protons produced by electron bombardment of H_2 in a Nier-type source are separated from the other ions by a 60° sector magnetic analyzer. The proton beam passes through a collimated beam of cesium atoms and some of the protons capture electrons. The $H(2s)$ atoms produced in this region drift out of the box containing the cesium oven and into a region where they are detected by quenching them in an electric field parallel to the beam and observing the Lyman-alpha radiation emitted. The Lyman-alpha detector[6] is an iodine-vapor-filled Geiger tube with a lithium fluoride window.

The electron gun opposite the Lyman-alpha detector allows the detector to be calibrated

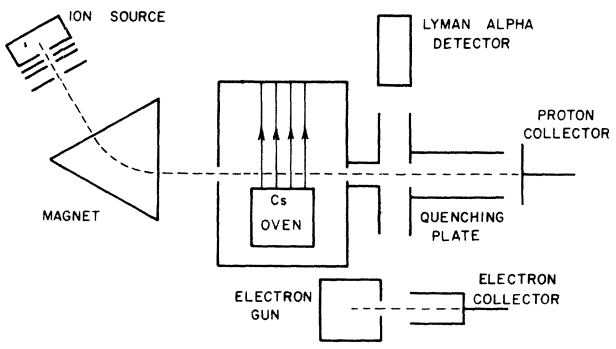

FIG. 1. A schematic diagram of the experiment.

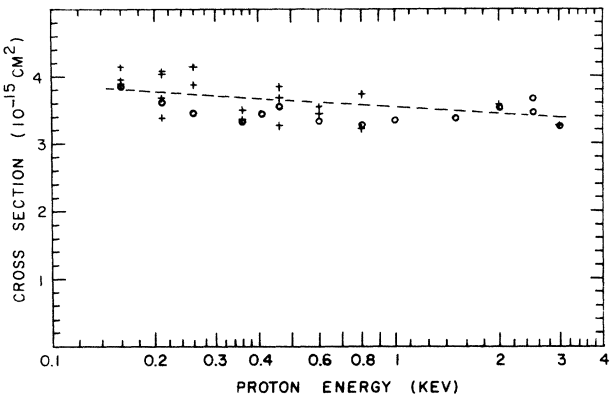

FIG. 2. Cross section for the nearly resonant reaction $H^+ + Cs \rightarrow H(2s) + Cs^+$.

using the reaction $e + H_2 \rightarrow$ Lyman alpha, the cross section for which has been determined by Fite and Brackmann.[7] The cesium beam intensity is determined by a surface ionization detector[8] placed just over the proton beam.

Figure 2 shows the measured cross sections for the reaction $H^+ + Cs \rightarrow H(2s) + Cs^+$. The various points plotted at a single energy are representative of the variation in data taken at different times. The reason for these fluctuations is not clearly determined, but are believed to be due primarily to the variation of the cesium beam during a run. The absolute cross section is believed to be accurate to within 50%.

With the cesium oven used in this experiment it was not possible to produce very high cesium densities in the interaction region, so it was not possible to raise the density to the point where quenching of the metastable atoms by the cesium was a significant effect. At the maximum cesium atom density used in this experiment, 0.3% of the protons were converted to metastable hydrogen atoms and since the yield of metastable atoms was a linear function of the cesium atom density over the range covered, it is likely that appreciably larger fractions of the protons can be converted to metastable hydrogen atoms merely by increasing the cesium atom density in the interaction region.

The principal difficulty encountered in trying to produce polarized protons by the Madansky and Owen scheme[1] was ionization of fast ground-state atoms in the residual gases, producing unpolarized protons which diluted the polarized protons obtained by ionizing the metastable hydrogen atoms with $m = \frac{1}{2}$. The reaction reported here might make feasible the Madansky and Owen scheme. (1) The metastable atoms would be at relatively low energy (say 500 eV) and thus could be separated more readily from the protons without quenching them. (2) Probably only a few ground-state atoms would be produced directly since the energy of the protons is well below the energy at which, according to the Massey relation,[4] the maximum cross section should occur for the reaction $H^+ + Cs \rightarrow H(1s) + Cs^+$. Some ground-state atoms are probably produced by the decay of atoms formed in the $2p$ states. (3) The ground-state atoms formed would be at a low energy so that the cross section for ionization in the background gases would be small. A nearly resonant charge exchange process such as $H(2s) + Cs^+ \rightarrow H^+ + Cs$ might be a good way of selectively ionizing the $H(2s)$ in lieu of photoionization as suggested by Madansky and Owen.

We would like to thank Professor Clayton Giese for calling our attention to the high cross sections associated with nearly resonant charge-exchange processes.

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