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Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions*

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Abstract

Foil stripping of H^- directly to H^+ is being considered for proton injection in the next generation of high-current proton storage rings. This technique can result in significant losses because excited states of H^0, which are also produced in the foil, are field stripped in the downstream bending magnets. Without due care in the injection system design, many of the resulting protons will be outside the acceptance of the storage ring and will be quickly lost. We measured the production of such H^0 excited states at the LAMPF High Resolution Atomic Beam Facility. An 800-MeV H^- beam was passed through carbon foils of thicknesses 70, 100, 200, and 300 $\mu g/cm^2$, and the excited states were analyzed by a special magnet downstream of the foil. The magnet had a linear field gradient so that the trajectories of the outgoing protons could be used to reconstruct the field values at which the various H^0 stripped. We found that about 1% of the H^0 emerge in excited states which can be stripped to protons by ring bending magnets.

I. INTRODUCTION

We have measured the production of excited neutral hydrogen atoms in a foil by studying their subsequent field ionization in a magnet. The foil thicknesses were comparable to those being used for injection into existing storage rings and to those being considered for storage rings at the next generation of spallation neutron sources. The linear field gradient magnet had a field shape similar to the fringe field in a ring-bending magnet. This experiment combined the efforts of the Proton Storage Ring (PSR) development group and a basic research group that has been doing accelerator-based atomic physics research at Los Alamos using laser ion colliding beams for the past twenty years [1].

The experiment took place at the High Resolution Atomic Beam Facility at LAMPF where a "laser quality" external H^- beam is available. The beam kinetic energy can be varied from 100 MeV to 800 Mev with typical beam parameters of 2 mm spot size, 100 μrad divergence, and 0.05% δp/p. With special tuning, these parameters can be improved to ~0.5 mm spot size, ~10 μrad divergence and 0.01% δp/p [2].

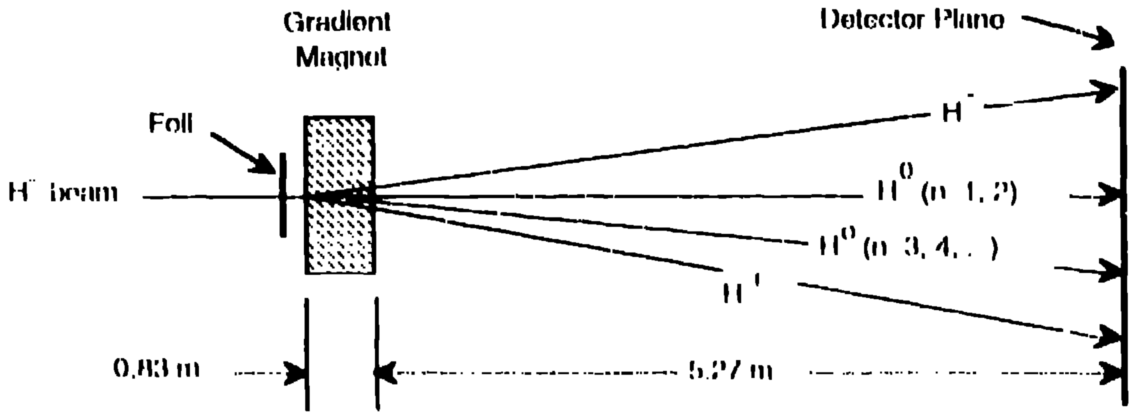

Figure 1 Layout of experiment to measure production of excited states

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When a beam of H^- ions strikes a foil, some ions are stripped of both electrons to become protons (H^+), some are stripped of one electron to become hydrogen atoms (H^0), and some pass through the foil unscathed. At the foil thickness of interest for injection, most will be H^+. Some of the H^0 will be produced with the bound electron in an excited state. The distribution of these excited states was the quantity to be determined by this experiment.

When the H^0 enter a magnetic field, they are subjected to a motional electric field in their rest frame. This field is given by

$$\mathbf{F} = (3\times10^6)\,\gamma\beta \times \mathbf{B}, \qquad (1)$$

where $\mathbf{F}$ is in V/m and $\mathbf{B}$ is in tesla. The symbols γ and β are the usual relativistic parameters of the beam. For an 800-MeV atom, β=0.842 and γ=1.85. Thus a magnetic field of 1 T transforms to an electric field of 4.7 MV/m in the rest frame of the atom.

This intense electric field causes the atom to become unstable since the electron can tunnel out through the potential barrier. Ionization will proceed rapidly at a critical field given, to first order, by

$$F_c\,[\mathrm{V/m}] = \frac{5.142\times10^{11}}{9n^4}, \qquad (2)$$

where n is the principal quantum number of the spherical states.

In the presence of a field, the states with definite lifetime are parabolic states represented by the quantum numbers (n1, n2, m) [3]. These are related to the spherical states (n, l, m) through the Clebsch Gordon coefficients. The principal quantum number is related to the parabolic quantum numbers by

$$n = n_1 + n_2 + m + 1. \qquad (3)$$

II. TECHNIQUE

We studied the excited states using a gradient magnet with a field that increases linearly with distance along the beam line. When a given H^0 state reaches the critical field, given by equation (2), it is stripped and the resulting H^+ is bent in the downstream magnetic field. The magnet is followed by a drift region and then a detector system. Knowing the field map of the magnet, we can then reconstruct the field at which a particular H^0 ionized. This technique and this same magnet have been used previously to study the ionization probability of the H^- ground state as a function of field [4].

The apparatus consisted of the foil box, the gradient magnet, a 5.27-m flight path and a detector system. The floor layout is shown in Fig. 1. The detector system consisted of a scintillator telescope, a multi-wire proportional chamber (MWPC), and a scanning scintillator. The scintillator telescope covers the entire beam so that the experiment can be properly normalized. Standard beam diagnostics and phase space tailoring apparatus are not shown.

The gradient magnet is a half quadrupole turned sideways to the beam. The beam enters through a hole in the return yoke and then encounters a vertical magnetic field whose strength increases linearly with distance. The maximum field available is 1.9 T and the length of the gradient region is 0.2 m.

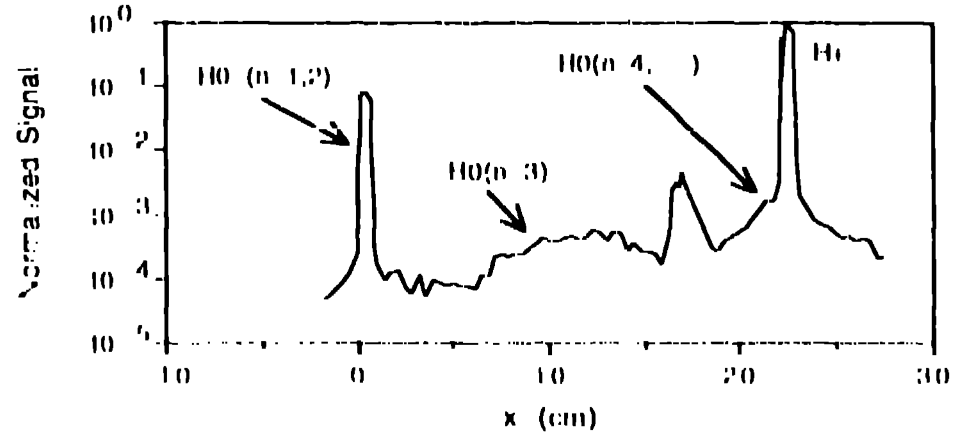

Figure 2. Typical data taken with the scanning scintillator and normalized to incident ions. The data shown are for a peak field of 1.5 Tesla and a foil thickness of 200 μg/cm². The sharp peak near 17.5 cm is believed to be spurious and will be investigated further during the 1993 run.

The data are analyzed using the Damburg-Kolosov (DK) formalism [5]. DK represent the unstable states as Breit-Wigner resonances and give a formula for the widths in terms of the field, the Stark-shifted energy of the state, and the parabolic quantum numbers. The Stark energy of the state are calculated from fifth-order perturbation theory.

We have tested the DK formalism by comparing to exact numerical calculations. These numerical calculations were verified in a previous experiment where we used a laser to excite the Stark states [6]. We found that the DK energies are accurate to 0.05% and the DK widths are accurate to better than 20% in the region of interest.

Our analysis code starts with a given distribution of excited states, finds out where they ionize using the DK formalism, and then traces the H^0 trajectories through the magnet and into the detector. The input parameters are then varied using a non-linear optimization code until a best fit is obtained. Many of the software subroutines were developed in a previous series of foil experiments [7].

III. RESULTS

The analysis program is still being tuned up, so precise numbers for the distribution of states are not yet available. We can see that the excited states that can be stripped in the downstream magnet are about 1% of the incident beam. This is enough to cause serious first turn losses in high current storage rings.

A typical data set is shown in Fig. 2. At this time, we believe that the sharp peak near $x=17.5$ cm is spurious and not an excited H^0 state. After subtracting this peak, the excited states are consistent with a statistical distribution in which sub states are populated equally.

IV. FUTURE WORK

We are planning an improved experiment for the fall of 1993. The next experiment will have a MWPC detector with larger aperture and capable of higher rates. An upstream laser beam will be used to produce H^0 in a well defined state so that we can track them through the magnet. This will allow us to verify the analysis code and look for systematic effects.

V. ACKNOWLEDGMENTS

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