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**DETERMINATION OF BEAM ORIENTATION OF
OPTICAL DIAGNOSTICS OF EXCITED 200-MeV
HYDROGEN ATOMS RESULTING FROM
PHOTODETACHMENT OF H⁻ IONS**

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September 1987

Final Report

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This technical report has been reviewed and is approved for publication.


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I. INTRODUCTION

At the onset of this project, a novel beam diagnostic technique, designed to measure beam profile, perpendicular velocity spread, and orientation of multi-MeV H^0 atoms produced by acceleration and photoneutralization of H^- beams, was to be investigated. But the importance of beam orientation over other parameters led to emphasizing this aspect of the effort. What seemed feasible before analysis proved to be impossible, while new ideas showed encouraging results as other avenues were explored; the objective thus became a conceptual development of nondestructive diagnostic techniques to determine the direction of a 200-MeV H^0 beam.

A number of methods based on excited hydrogen atoms are analyzed. They begin with the neutralization of H^- ions with a laser whose wavelength is such that the photodetachment process results in the formation of excited hydrogen atoms in either the $n=2$ level, or the $n=3$ level. The methods can be grouped into two categories: [1] direct optical measurements of Lyman-alpha radiation emitted by $H^*(2p)$, and [2] production of $H^*(2s)$ or $H^*(3p)$ atoms for schemes already proposed requiring the availability of these excited atoms.

Measuring the total fluorescence of Lyman-alpha radiation from $H^*(n=2)$ levels can be easily used to determine beam direction to within 40 μ rad.

Lyman-alpha radiation can also be used to either measure minute Doppler shifts to detect small angular variations, or to spatially resolve the trajectory of a beam element by measuring spatial intensities. Calculations of minute Doppler shifts of the Lyman-alpha radiation indicate that a resolution of $\Delta\lambda/\lambda$ of 10^{-6} , which can be measured by spectrograph, could sense angular changes of 2.8 μ rad in beam orientation. However, any spatial intensity or velocity spread measurements would not have a high enough resolution to be of any interest.

Sources of photodetachment-produced $H^*(2s)$ and $H^*(3p)$ can greatly benefit the proposed laser resonance fluorescence (LRF) technique and the

Doppler shift sensing technique, respectively. There are many advantages to producing excited hydrogen atoms with photodetachment rather than collisional detachment. The two most important are the elimination of cascading, especially in the laser resonance fluorescence technique, and the actual production of $H^*(3p)$ atoms for the Doppler shift sensing technique (since no satisfactory source has yet been identified for it).

Technically, most aspects of this scheme require instruments which are at the "cutting edge" of present day technology. These devices are discussed with each scheme. However, the most important apparatus is the laser. Suitable lasers have been identified: an e^- beam driven argon fluoride (ArF) laser which emits at 1930 \AA for the shape resonances, i.e., to excited $H^*(2p)$ and $H^*(2s)$; and, a xenon laser emitting at 1750 \AA which can photodetach $200 \text{ MeV } H^-$ to form $H^*(3p)$ atoms. Additionally, a hot cathode e^- beam driver is needed for an ArF laser to produce $H^*(2s)$ atoms in a quantity comparable to that of a gas neutralizer. The physical principles on which this scheme is based are well known. However, the various cross sections, and in particular the partial cross sections, are known quantitatively but not very accurately. Nevertheless, some adequate estimates are discussed in the next section.

II. RELEVANT CROSS SECTIONS

The process under consideration is



with the hydrogen atom left in either the $n=2$ or the $n=3$ level. The photodetachment cross section has resonances. The $n=2$ resonance is known as the shape resonance. As the following literature review indicates, the total cross sections are known and there is a reasonable agreement between theory and experiments. However, the branching ratio of each total cross section is not known. One can nevertheless make a good guess which should be better than 50%. Since this is a feasibility study, a very accurate numerical value of each partial cross section is not needed. Thus, the values of σ_{2s} , σ_{2p} and σ_{3p} which are arrived upon at the end of this section, should be well within an order of magnitude of their actual value, and certainly more than adequate for a feasibility study.

1. PARTIAL CROSS SECTIONS IN THE SHAPE RESONANCE

The threshold for production of $H^*(n=2)$ lies at 10.959 eV. Immediately above this threshold are three possible final states: $1s$, $2s$ and $2p$ for which the formation cross sections are σ_{1s} , σ_{2s} , and σ_{2p} . Two-electron detachment is of course not possible for photon energies below 14.3650 eV, the binding energy of H^- .

Just above the $n=2$ threshold lies the shape resonance which has $1p^0$ symmetry and can be excited from the ground state by an electric dipole interaction. The most reliable calculations of its position are probably those of Broad and Reinhart (Ref. 1) and Taylor and Burke (Ref. 2) as analyzed by Macek and Burke (Ref. 3). Broad and Reinhardt find that the shape resonance lies at 10.977 eV, 18 meV above the $n=2$ threshold, in excellent agreement with Taylor and Burke. This value was calculated assuming an

infinitely heavy proton. In the case of a highly correlated system such as H^- , the nuclear recoil correction is not simply a matter of scaling the energy by $(1-m/M)$ and the corrected value has an uncertainty of m/M . Thus, the photon energy required to excite the peak of the shape resonance is

$$E_{\gamma} = 10.977 \text{ eV} \quad (1)$$

and the wavelength is

$$\lambda = 1130.1 \text{ \AA} = 113.01 \text{ nm} \quad (2)$$

The position of this resonance relative to the I_p Feshbach resonance below $n=2$ has been confirmed experimentally by Bryant, et al (Ref. 4), but the absolute position was not measured.

According to Broad and Reinhardt (Ref. 1), the cross section at the peak of this resonance is $3.4a_0^2$ ($9.5 \times 10^{-17} \text{ cm}^2$) and the width is 15 meV. Taylor and Burke (Ref. 2) find a width of 14 meV in good agreement but do not calculate a cross section. The experiments of Bryant, et al., (Refs. 4-5), do not determine absolute cross sections; but when their data are normalized in the low energy continuum so as to agree with Broad and Reinhardt's value there, the measured cross section at the peak of the shape resonance is completely consistent with theory. Figure 1, taken from Reference 5, shows this comparison. Unfortunately, the width of the theoretical curve seems to be too narrow. One cannot simply ascribe the difference to instrumental broadening of the measured line, because the instrumental width is known from the width of the Feshbach resonance, also shown in Figure 1. Thus the best values to take are probably the theoretical cross section

$$\sigma = 9.5 \times 10^{-17} \text{ cm}^2 \quad (3)$$

and the measured width

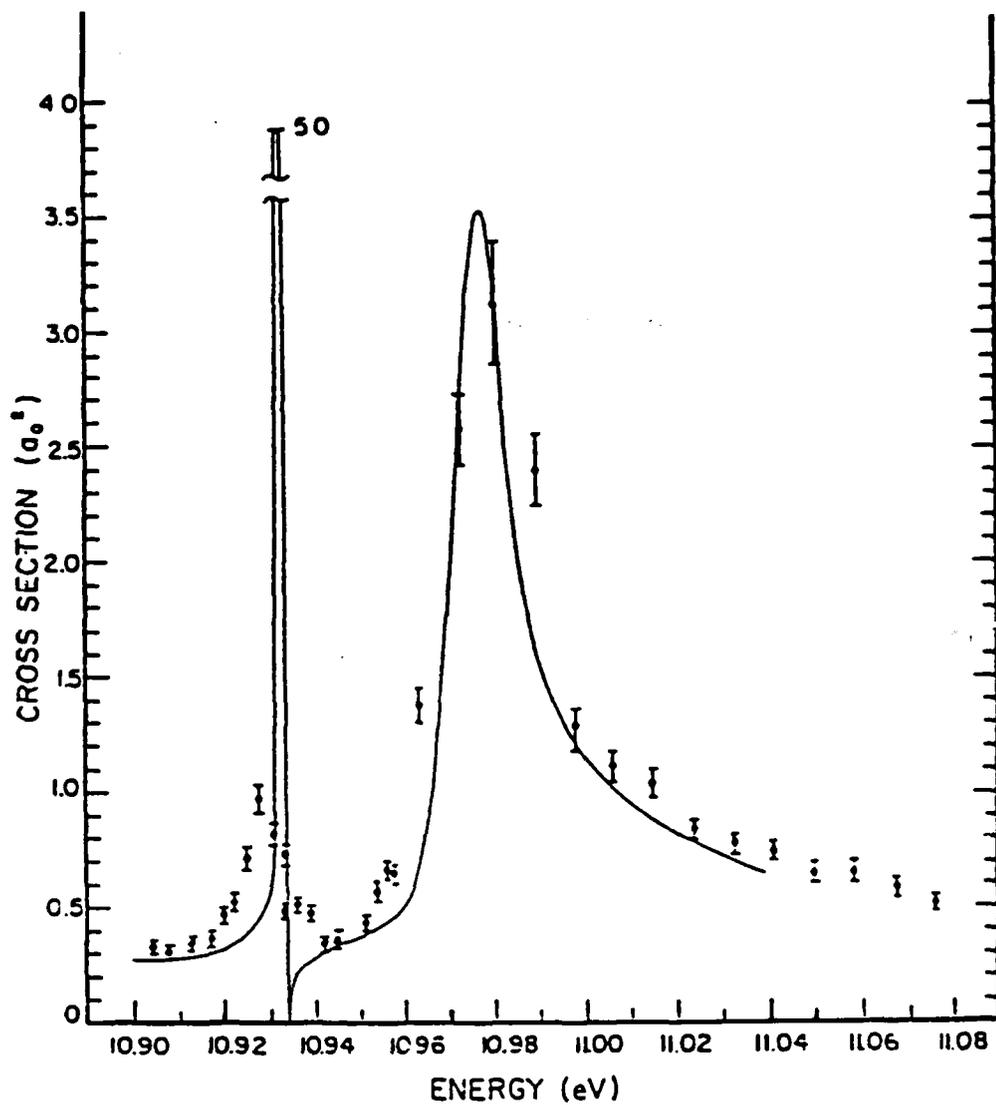


Figure 1. Comparison of theory (Ref. 1) and experiment (Ref. 5). The measured cross section is normalized to the theory at 10.9 eV. The error bars are statistical only. (Taken from Ref. 5.)

$$\Delta E_{\gamma} = 23 \text{ meV} \quad (4)$$

or

$$\Delta\lambda = 2.4 \text{ \AA} \quad (5)$$

We now turn to the partial cross sections σ_{1s} , σ_{2s} and σ_{2p} . The only attempt to calculate these cross sections separately was made by Hyman, Jacobs, and Burke (Ref. 6). In their theory, the final state wavefunctions did not include any electron-electron correlation terms and therefore both the width and the position of the shape resonance were expected to be wrong (Ref. 2). However, Macek has argued (Ref. 7) that the oscillator strength should be fairly insensitive to the absence of these terms and hence that the area under the calculated shape resonance should be correct. To test this view one can consider the shape resonance calculated without electron correlations by Macek (Ref. 7), which is 85 meV wide and has a peak cross section of $2.7 \times 10^{-17} \text{ cm}^2$. Of this, $2.1 \times 10^{-17} \text{ cm}^2$ is resonant and the rest is a background continuum. After scaling the resonant part to the measured width of 23 meV in such a way as to preserve the area under it, the peak total cross section becomes $8.4 \times 10^{-17} \text{ cm}^2$ in moderately good agreement with the value given in Equation 3. Figure 2 shows the partial cross sections calculated by Hyman, Jacobs and Burke (Ref. 6). The sum of these partial cross sections is in almost exact agreement with the total cross section calculated by Macek (Ref. 7), and hence gives essentially the correct cross section after scaling as described above. It seems reasonable, therefore, to suppose that the partial cross sections are also correct after such a scaling. However, it is not clear how to do the scaling correctly, since the partial cross sections do not all vary with energy in the same way. Instead, consider the peak cross sections which have the ratio

$$\frac{\sigma_{2p}^D}{\sigma_{1s}^D} : \frac{\sigma_{2p}^D}{\sigma_{2s}^D} = 4:3:1$$

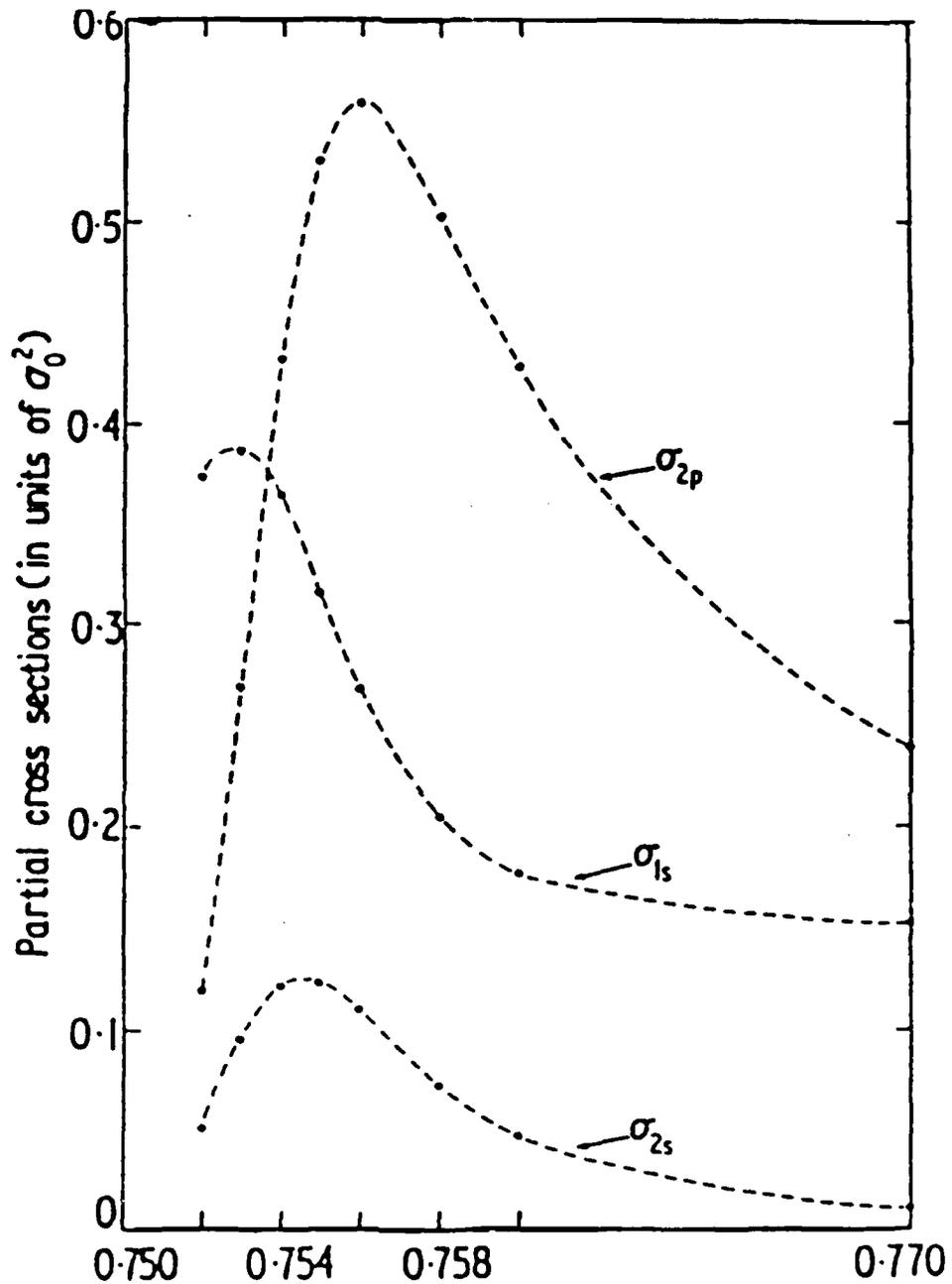


Figure 2. Theoretical partial cross sections for formation of 1s, 2s and 2p states of hydrogen by photodetachment of H^- . (The abscissa is the photon energy in Rydbergs. The ordinate is the partial cross section in units of the Bohr radius squared.) (Taken from Ref. 6.)

In the absence of any more detailed knowledge, it is not unreasonable to suppose that the true partial cross sections are related in roughly the same way. This point of view is supported by the measurements of Krause and Wuilleumier (Refs. 8-9) who studied the angular distribution of electrons photodetached from He in the resonance above the $n=2$ threshold. This system is very similar to the one of interest here. From their data, they deduced a value for σ_{2p}/σ_{2s} in agreement with the ratio of peak cross sections calculated for negative hydrogen (Ref. 6). We therefore take the following values

$$\sigma_{2p}^p = 4.8 \times 10^{-17} \text{ cm}^2 \quad (6)$$

$$\sigma_{2s}^p = 1.2 \times 10^{-17} \text{ cm}^2 \quad (7)$$

$$\sigma_{1s}^p = 3.6 \times 10^{-17} \text{ cm}^2 \quad (8)$$

These values are qualitatively consistent with Broad and Reinhardt's "very reasonable estimates" (Fig. 6 of Ref. 1) which give

$$\sigma_{2s} + \sigma_{2p} = 6.4 \times 10^{-17} \text{ cm}^2 \quad (9)$$

and

$$\sigma_{1s} = 3.1 \times 10^{-17} \text{ cm}^2 \quad (10)$$

Practically, the values given in Equations 6, 7, and 8 should be adequate for any system of interest since the laser wavelength is chosen to match the peak of the partial cross section for the required process and since any system of interest would have a beam of extremely low emittance.

2. THE $n=3$ RESONANCE

Hamm, et al. (Ref. 10), have investigated experimentally the H^- photodetachment cross section near the $n=3$ threshold and have shown agreement with theoretical calculations (Ref. 11). These studies focused on the structure (two dips) before the $n=3$ threshold, although the $n=3$ threshold was investigated as well. From the experimental results (Ref. 10), the cross section for $H^- + \gamma \rightarrow H^*(n=3) + e^-$ is

$$\sigma_{n=3} = 8.4 \times 10^{-18} \text{ cm}^2 \quad (11)$$

for a photon energy of 12.85 eV. The branching ratio of $n=3$ into 3p, 3s, and 3d has never been calculated (Ref. 12). However, a good guess would be (Ref. 12) that the 3p and 3s states are comparably excited with only less than 20% of the $n=3$ atoms in the 3d state and the rest equally divided into the 3p and 3s states, i.e.,

$$\sigma_{3p} = 3.36 \times 10^{-18} \text{ cm}^2 \quad (12)$$

III. EXPERIMENTAL ARRANGEMENT

A possible experimental arrangement is shown in Figure 3. Beam parameters from the low divergence Neutral Beam Test Facility now under construction at BNL are used to illustrate this method. A vacuum ultraviolet laser intersects this low divergence H^- beam at an angle θ . The laser wavelength and its orientation (the angle θ) are determined from the desired photodetachment products and the most powerful laser in the acceptable wavelength range.

1. H^- BEAM PARAMETERS

Reference 13 is a proposal for a neutralizer test facility and beam sensing and control experiment facility. On this basis, the Neutral Beam Test Facility (NBTF) is being constructed at BNL. Beam parameters from Ref. 13 are used throughout this work to compute photodetachment products. Table 4-1 from Ref. 13 contains the following beam parameters: beam current 0.9 mA, pulse length 0.5 msec. The beam has an elliptical cross section with major axis of 9.1 mm and minor axis of 50 mm.

2. VACUUM ULTRAVIOLET LASERS

In order to excite the shape resonance, a 113-nm laser is required for a cross-beam experiment. At this wavelength only very short pulse moderate power lasers exist (Ref. 14). However, for fast H^- beams, other lasers can be used. If the wavelength of the laser is λ_0 , we can use the Doppler shift to give the required 113 nm in the frame of reference of the ion beam by correctly choosing the angle between the two beams. Let that angle be θ ; i.e., $\theta=0$ for the beams are parallel. Then the correct angle is given by

$$\cos\theta = \frac{1}{\beta} \left(1 - \frac{\lambda_0}{113\gamma} \right) \quad (13)$$

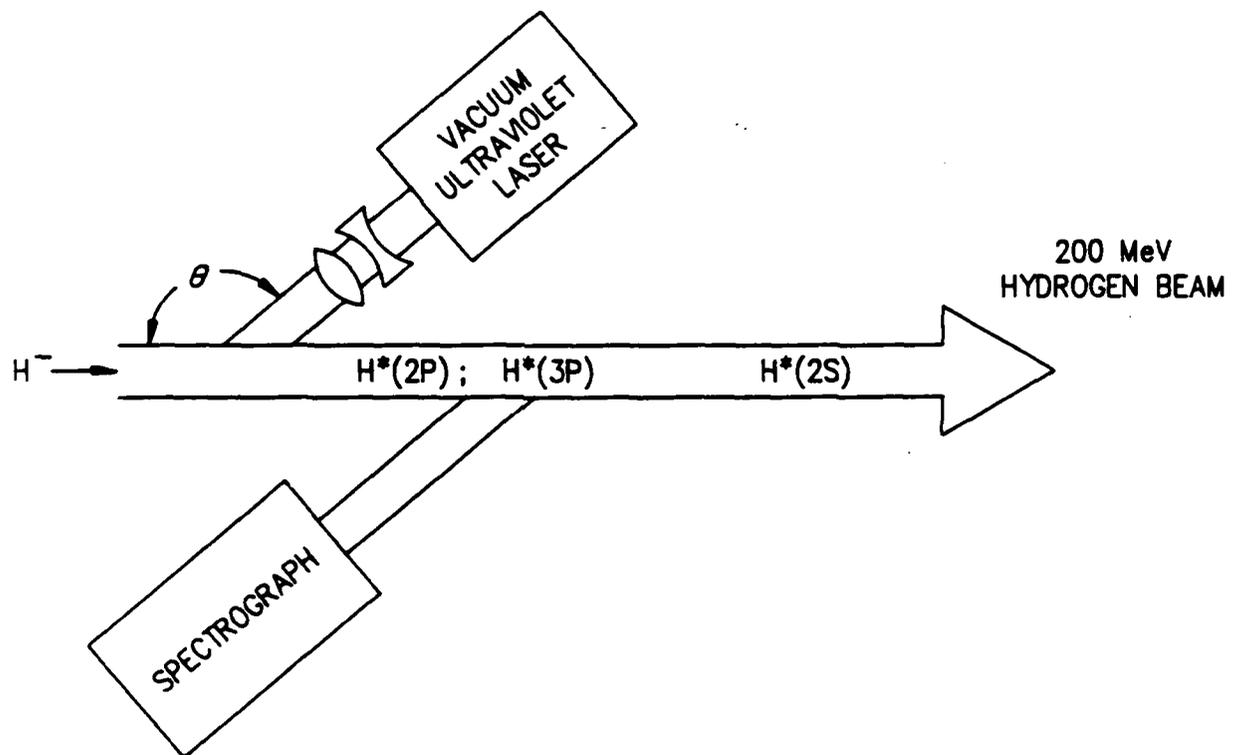


Figure 3. Schematic of a possible experimental system.

where $\beta = v/c$ and $\gamma = (1-\beta^2)^{-\frac{1}{2}}$ are the usual parameters of special relativity. They are related to the ion beam energy by

$$\gamma = \epsilon + 1 \quad (14)$$

$$\beta = \left[1 - \frac{1}{(\epsilon+1)^2} \right]^{\frac{1}{2}} \quad (15)$$

where ϵ is the beam energy in MeV divided by 938. Figure 4 shows the variation of λ_0 with ϵ for various beam energies.

In our case of a 200-MeV H^- beam, Equations 14 and 15 give $\beta = 0.566$, $\gamma = 1.213$. The possible laser wavelengths for exciting the shape resonance in this beam lie between 214 nm ($\epsilon = 180$) and 60 nm ($\epsilon = 0$) as calculated from Equation 13 and shown in Figure 4. In this wavelength range, the ArF excimer laser operating at 193 nm is best. According to Equation 12, the correct angle for Doppler tuning is $\theta = 136.1^\circ$. Normally, these lasers have very short pulses (~ 30 ns). Maxwell Laboratories, Inc., located at 8888 Balboa Avenue, San Diego, CA, manufactures electron beam driven lasers with microsecond pulse lengths. This company can make a 10-J, e-beam driven ArF laser with a 5- μ s pulse duration at a cost of about \$250,000. They conceivably can stretch these numbers to as high as 100 J and 10 μ s. As will become obvious, the power levels are more than sufficient, but it is desirable to expand the pulse length. This would require the use of hot cathodes in the e-beam systems for which there is no data base; all present systems have cold cathodes. Increasing the pulse length to 100 μ s is in principle possible, but it would need some basic research and development to determine its feasibility. The laser beam has a 10-cm x 10-cm cross section which can be focused to the size of the H^- beam with the use of CaF_2 lens. Thus, one can purchase a 2-MW ArF laser with a pulse length of 5 μ s from Maxwell Laboratories, Inc., at a cost of about \$250,000. And, in principle, they can develop a larger version of this laser with a power of 10 MW and double the pulse length.

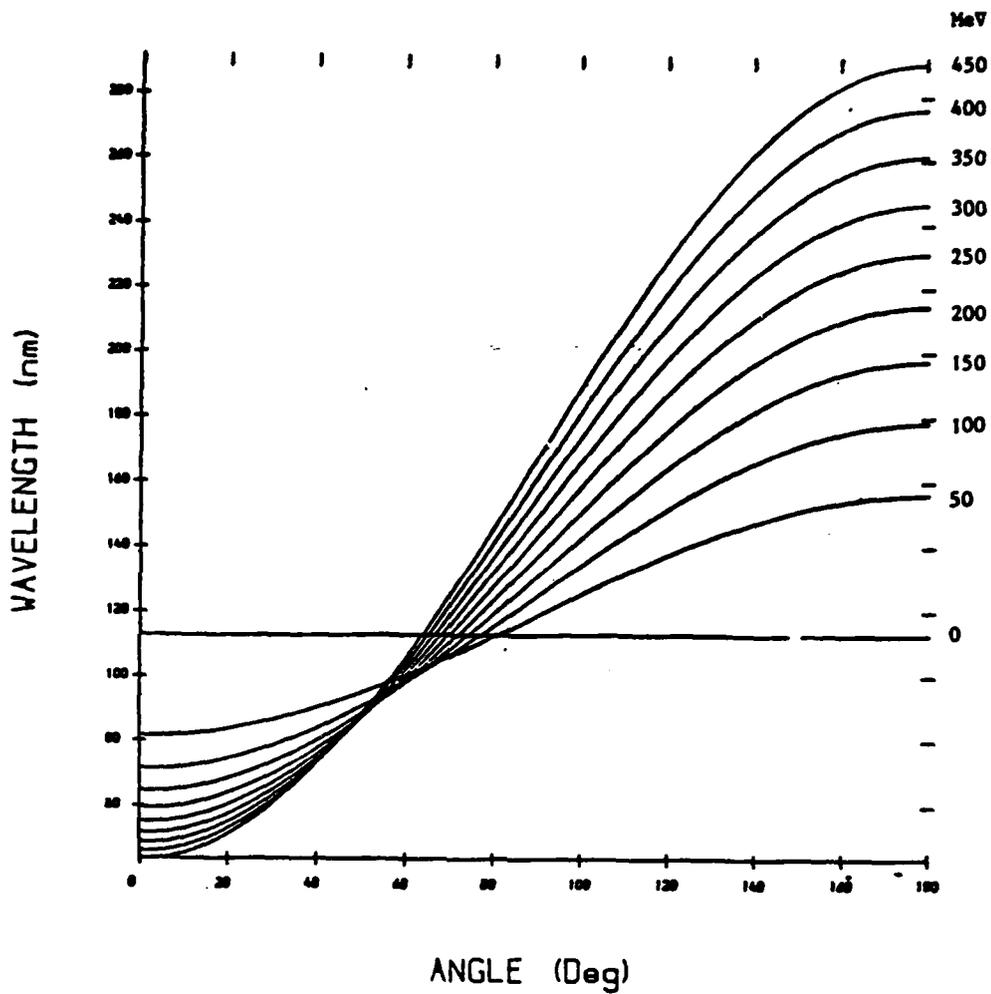


Figure 4. Wavelength required to excite the shape resonance vs. angle between laser beam and particle beam for various values of particle beam energy.

Similarly a KrF laser, which operates at 249 nm and has demonstrated considerably more power, could be used at $\theta = 140^\circ$ with a 400-MeV beam. This laser practically an off-the-shelf item from Maxwell Laboratories, Inc.

To photodetach H^- ions leaving the residual hydrogen atom in an $n=3$ state, the photon in the rest frame of the beam must have a wavelength of 96.48 nm. Using Equation 13, replacing 113 by 96.5 to calculate the usable wavelength range for excitation of the $n=3$ resonance on a 200-MeV beam, one obtains a range of 185.25 nm ($\theta=180^\circ$) to 51.34 nm ($\theta=0$). The best laser to use is a xenon laser at 175 nm. At this wavelength, $\theta=151.06^\circ$. Although power levels exceeding 10^8 W are available from these lasers, their pulse length cannot exceed 50 ns due to the need of high e-beam currents which "load up" the foils thermally. Xenon lasers require electron beam current densities of 100 A/cm² for peak power output. For comparison, ArF lasers need only 5-15 A/cm². Thus, for 200-MeV beams, one can use Xe lasers with pulse lengths of up to 50 ns. But for 400-MeV beams, one can use ArF lasers with much longer pulse lengths.

IV. GENERATION OF EXCITED HYDROGEN ATOM BY PHOTODETACHMENT OF H⁻ IONS

When an H⁻ beam undergoes photodetachment, its current reduces as

$$I = I_0 \exp(-\sigma\Gamma\tau) \quad (16)$$

where σ is the total photodetachment cross section, τ is the interaction time and Γ (photons/cm²-s) is the photon flux. If the value of the exponent of Equation 16 reaches 1, less than 37% of the ions are left intact and over 63% of the beam is stripped. For exponent values approaching 3 to 4, the beam can be considered fully stripped.

Lasers considered in the previous section have a beam width of 10 cm, and orientation of $\theta \sim 150^\circ$. This means that a laser faces the H⁻ beam at 30° off the beam axis. Therefore, the interaction length, which is the beam length illuminated by the laser, is equal to $10 \text{ cm}/\sin(180-\theta) = 20 \text{ cm}$. Since the beam $\beta=0.566$, the interaction time over that length is $\tau \sim 1.2 \text{ ns}$. The total cross section σ for the shape resonance is about 10^{-16} cm^2 . Therefore in order for $\sigma\Gamma\tau$ to exceed unity, the photon flux needed is $\Gamma \geq 1/\sigma\tau$, or $\Gamma \geq 8.3 \times 10^{24} \text{ photon/cm}^2\text{-s}$.

Each one of the photons from an Xe or an ArF laser carries an energy of about 7 eV and 6.4 eV, respectively. Therefore, a photon flux of $8.3 \times 10^{24} \text{ photons/cm}^2\text{-s}$ corresponds to 9.3 MW/cm^2 for an Xe laser and 8.5 MW/cm^2 for an ArF laser. In the preceding calculation and conversion from photons/second to watt is based on $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ and $1 \text{ J/s} = 1 \text{ W}$. The current distribution of the NBTf H⁻ beam is not described in Ref. 13, but will probably be Gaussian, i.e., highly concentrated in the center. If the smaller of the transverse dimensions of the beam (9.1 mm) is irradiated by the laser, then illuminating 1 cm of beam height suffices to expose practically all the H⁻ ions to the laser light. Thus, one of the laser beam dimensions would be focused to 1 cm. Since the unfocused beam dimension is 10 cm, the total area to be irradiated is 10 cm^2 . Consequently, the laser power needed to photodetach the vast majority of H⁻ ions is

under 100 MW (93 MW for Xe and 85 MW for ArF). Both of these lasers have demonstrated power levels which are even higher than 100 MW. Hence, to a first approximation, it can be assumed that the H^- beam can be fully neutralized for the duration of the laser pulse.

1. $H^*(2s)$ FOR LASER RESONANCE FLUORESCENCE

In LRF, $H^*(2s)$ atoms are raised to the 3p level with a laser, and the resultant decay is observed. Two channels of decay are possible: either the H_α to the 2p state, or the much stronger Lyman-beta to ground. Many proposals for testing the LRF technique rely on the availability of $H^*(2s)$ atoms resulting from H^- neutralization in a gas cell. At best, only 50% of the H^- ions can be neutralized and only 6% of the neutral hydrogen atoms will be in the 2s state. Thus, under the most optimistic conditions, only 3% of the H^- ions can be neutralized on the 2s level in a gas cell. In addition, many problems such as cascading and other particles exiting the neutralizer result in difficulties for fluorescence detection. Pegg's analysis (Ref. 16) of LRF describes these difficulties and the desirability of $H^*(2s)$ atoms resulting from photodetachment.

To evaluate the full merit of utilizing photodetachment-produced $H^*(2s)$ in LRF, a quantitative comparison of the $H^*(2s)$ yield must also be done. Under the most optimistic conditions, using an ArF laser in NBT, the H^- beam can be almost completely photodetached using the shape resonance. From the partial cross section discussions in Section II, Equations 6 through 10, close to 13% of the neutral atoms emerging from the stripper are expected to be in the 2s state, i.e., about 13% of the original H^- beam could result in $H^*(2s)$. However, the H^- pulse length is 500 μs , and with some development, the ArF laser pulse could be stretched to 10 μs (from the already achieved 5 μs), while a gas cell is active for the full duration of the beam pulse. Thus, H^- photodetachment by the ArF laser has a maximum duty factor of 0.02, during the H^- pulse. Taking this into account, a maximum of 0.26% of the H^- could be photodetached to $H^*(2s)$ in a single pulse. If, however, a hot cathode e^- beam ArF laser with 100- μs pulse length is developed, the fraction of $H^*(2s)$ atoms will raise to 2.6%.

Estimates of the most optimistic $H^*(2s)$ yields from a gas cell and from a hot cathode, e- beam driven, ArF laser stripper show comparable yields per H^- pulse of 3% for the gas cell and of 2.6% for the ArF laser stripper. Consequently, if such an ArF laser becomes available, it could supply an LRF setup in NBTf with $H^*(2s)$ beam in a quantity comparable to any gas cell but of much better quality.

2. LYMAN ALPHA EMISSION FROM A PHOTODETACHED H^- BEAM

According to the partial cross sections discussed in Section II, Equations 6 - 10, over 50% of the neutral atoms emerge in the 2p state. These atoms decay spontaneously with a rest-frame lifetime of 1.56 μs at a mean distance of the 32 cm downstream from the laser beam.

The large homogenous width of the shape resonance ($\Delta\lambda/\lambda = 0.2\%$) is an advantage in this stripping scheme. It would take a large (~ 4 mrad) divergence in one of the beams or a 0.3% velocity spread (1.2 MeV energy spread) in the ion beam to create a comparable inhomogeneous width. Thus there is no particular virtue in using the so-called magic angle $\theta = \cos^{-1}(\beta)$ where the first order Doppler width vanishes.

On the other hand, the shape resonance is by no means insensitive to the angle between the two beams, and thus the neutralizer itself provides information which could be used in a feedback loop to stabilize the particle beam orientation. In view of the large amount of fluorescence from the neutral beam (2p-1s decay), stability to 1% of the shape resonance linewidth (40 μrad) should be readily achieved. While this method of steering is not as accurate as an auxiliary direction monitor, such as one based on the 2s-3p transition, it has the obvious virtue of simplicity.

The fluorescence from the beam carries information about the beam direction, both in the wavelength distribution and in the intensity distribution. At first glance, sensing intensity distribution and following a

path traced by radiation has a qualitative appeal. A minor objection to using the intensity distribution of the spontaneous fluorescence as a direction monitor is that the low-energy intensity distribution is not known. The 2p state of hydrogen will inevitably have some alignment along the electric field axis of the light which leads to a nonspherical low-energy intensity distribution. This is not serious because the alignment could be measured and taken into account. If a static field is used to induce decay of the 2s atoms, the angular distribution is well understood (Refs. 17 - 18). But, due to the branching ratio of the cross section, the intensity of the induced Lyman-alpha decay from $H^*(2s)$ is only 25% of the spontaneous $H^*(2p)$ decay.

The major objection is a matter of signal intensity. If we want to know the angle between the particle beam and some reference direction with an accuracy of say $\Delta\theta$ rad, the fluorescence must be collimated along that direction into a solid angle of $(\Delta\theta)^2$ sr. With tight collimation, the detector will be able to view only a small part of the beam. For example, when the detector is 100 cm from the beam, the viewing area is $(100 \Delta\theta)^2$ cm². For a 1-cm-height sampling of the beam, the probability of an atom decaying in front of this window is $\frac{(100 \Delta\theta)^2}{32}$ (decay length = 32 cm) and only some $(\Delta\theta)^2/4\pi$ of these decays will be into the chosen direction. The light must then be analyzed for intensity with perhaps 10% efficiency. The H^- current density is not known at present. It lies between two extremes: a Gaussian profile which yields an H^- current density in the center of 5.4 mA/cm² as an upper limit, and a uniform distribution of 25.2 μ A/cm² as a lower limit. Since 50% of the neutralized atoms are in the 2p level, the $H^*(2p)$ peak flux could be as high as 1.7×10^{16} atoms/cm²-s. But the viewing area is only $(100 \Delta\theta)^2$, and the various geometric, efficiency, and decay probability factors reduce the number of detected photons by a factor of $2.5/(\Delta\theta)^4$. Altogether, $1.7 \times 10^{16} \times 2.5 \times 10^4 \times (\Delta\theta)^6$ photons/s can be detected. If the $H^*(2p)$ beam were steady-state, and only 10 photons/s were to be detected, then the resolution $\Delta\theta$ would have been 5.35×10^{-4} rad. We do not even have a steady-state H^- beam, which makes even a mrad resolution in intensity measurements unthinkable.

In Section IV, Doppler shift measurements are analyzed.

3. GENERATION OF $H^*(3p)$ ATOMS

From the discussion in Section II, the cross section for H^- photo-detachment at $n=3$ resonance is an order of magnitude lower than at the shape resonance. Therefore, power requirements for the Xe laser are a factor of 10 higher. Nevertheless, power levels of about 10^9 W are either feasible or have been demonstrated with Xe lasers for pulse duration of up to 50 ns. The proposed Doppler shift sensing technique needs $H^*(3p)$ atoms to study Doppler shifts in $3p-2s$ decay photons. No satisfactory source of $H^*(3p)$ has been identified in that proposal.

A 10^9 -W, 50-ns pulse from an Xe laser can fully neutralize the H^- beam, yielding 5.6×10^{15} $H^0(n=3)$ /s. For a 50-ns pulse duration, one obtains 2.8×10^8 $H^*(n=3)$ atoms per pulse. Given the partial cross sections estimated in Section II, the $H^*(3p)$ yield could be as high as 1.125×10^8 $H^*(3p)$ atoms/pulse. This yield, when compared to an estimated 3.4×10^6 $H^*(3p)$ /macro-pulse obtainable for LRF (Ref. 13), is a factor of the 33 higher and does not require the use of a potentially troublesome gas cell. For 400-MeV H^- beam, lasers like ArF and KrF with much longer pulse durations could be used, yielding orders of magnitude more $n=3$ hydrogen atoms per pulse.

V. MEASUREMENTS OF MINUTE DOPPLER SHIFTS IN LYMAN-ALPHA DUE TO SMALL ANGULAR CHANGES IN BEAM ORIENTATION

The 2p-1s decay wavelength is 121.6 nm in the rest frame of the atoms. Thus in the laboratory frame the observed wavelength depends on the angle of emission relative to the beam velocity in the following way,

$$\lambda = 121.6 \gamma(1 - \beta \cos \theta) \text{ nm} \quad (17)$$

where again $\theta=0$ corresponds to the direction parallel to the particle beam. Figure 5 shows the variation of λ with particle beam energy and angle of emission. In our example of a 200-MeV beam, the decay radiation spans the large wavelength range 64-231 nm.

There is also a relativistic modification of the intensity distribution; the low-energy probability of decay at an angle θ into solid angle d is multiplied at high beam energy by the relativistic factor R

$$R = \frac{1}{\gamma(1-\cos \theta)} \quad (18)$$

Figure 6 shows R as a function of θ for various beam energies. In the special case of isotropic decay, where the probability of emission at low energy is independent of θ , Figure 7 represents the intensity distribution itself.

The Doppler shift formula, which is equivalent to, but more general than, Equation 13 is

$$\nu = \nu_0 \gamma(1 + \beta \cos \theta) \quad (19)$$

For very small angular changes

$$\Delta \nu \approx d\nu = -\nu_0 \gamma \beta \sin \theta d\theta \approx \nu_0 \gamma \beta \sin \theta \Delta \theta \quad (20)$$

Using the first and last terms of Equation 20, converting from Δ to $\Delta\lambda$ and solving for $\Delta\lambda$, one obtains

$$\Delta\lambda = \frac{C}{v + \Delta v} - \frac{C}{v}$$

or

$$\Delta\lambda = \frac{C}{\gamma v_0(1 + \beta \cos\theta - \beta \sin\theta \Delta\theta)} - \frac{C}{\gamma v_0(1 + \beta \cos\theta)} \quad (21)$$

From Equation 21, $\Delta\lambda/\lambda$ can be calculated to obtain for very small $\Delta\theta$ (neglecting corrections which are order of magnitudes lower),

$$\frac{\Delta\lambda}{\lambda} = \left| \frac{\beta \cos\theta}{1 + \beta \cos\theta} \Delta\theta \right| \quad (22)$$

To measure minute Doppler shifts, detection devices must be oriented at the so-called "magic angle" determined when $\cos\theta = \beta$ in order to avoid $\Delta\beta$ broadening. For our 200-MeV beam, this occurs at $\theta = 55.5^\circ$. At this angle, the Lyman-alpha radiation has a wavelength of 1926.66 \AA . And, the relativistic correction factor $R = 0.65$ (from Eq. 18 and Fig. 7). For these values a Doppler shift measurement with $\Delta\lambda/\lambda = 10^{-6}$ would yield from Equation 22 $\Delta\theta = 2.8 \text{ \mu rad}$. This kind of resolution (of $\Delta\lambda \approx 0.002 \text{ \AA}$) at this wavelength can be reached in a spectrograph. McPherson Instruments, located at 530 Main Street, Acton, Massachusetts, has been building spectrographs for many years. Therefore, I asked them to examine the feasibility of fabricating a spectrograph to perform this type of measurement. I have given them the pertinent parameters of the Lyman-alpha radiation and the spectrograph orientation, i.e., $2.8 \times 10^{10} \text{ H}^*(2p)$ per pulse, $\theta = 55.5^\circ$, for the spectrograph at which angle $\lambda = 1926.66 \text{ \AA}$ and $R = 0.65$. From these values and the instrumental and geometrical losses, one can estimate the feasibility. The number of $\text{H}^*(2p)$ per pulse is based on the fact that 50% of the neutralized H^- ions are in the 2p level and on a neutralizing laser (ArF) pulse duration of 10 μs .

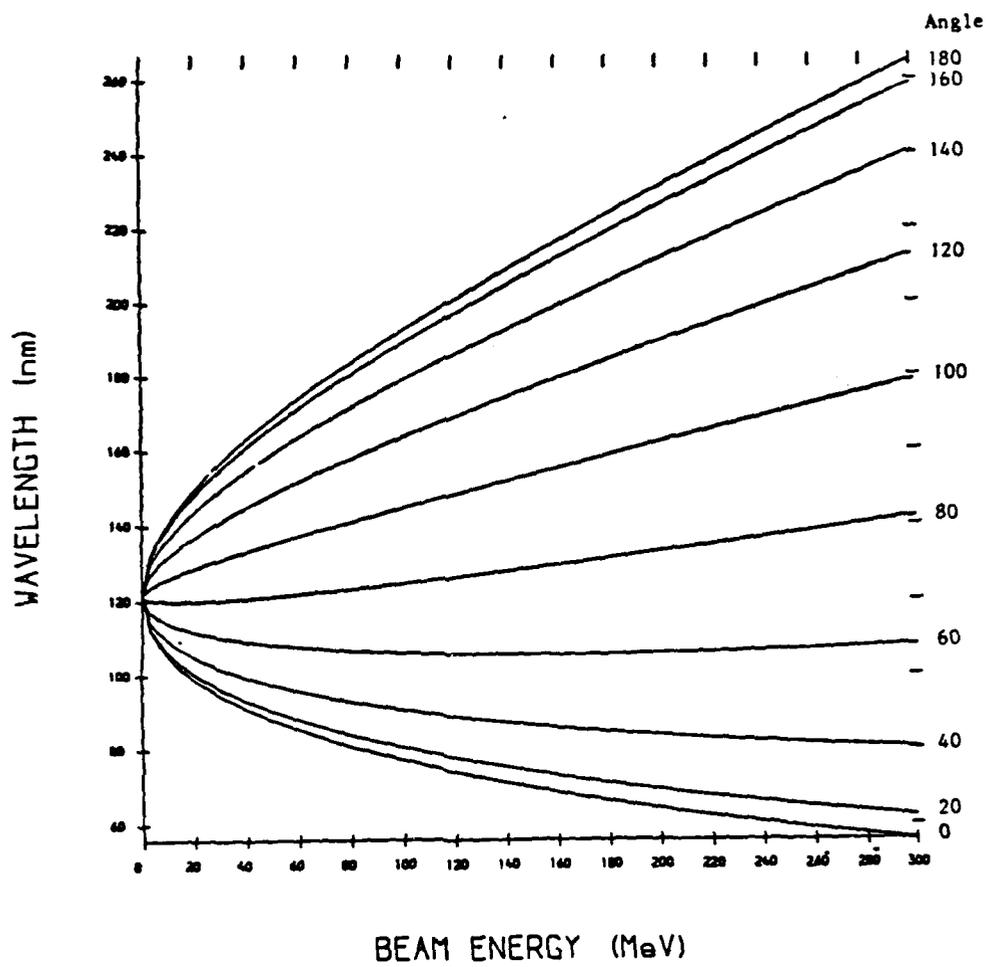


Figure 6. Wavelength of Ly- α fluorescence vs. particle beam energy for various angles between fluorescent light and particle beam.

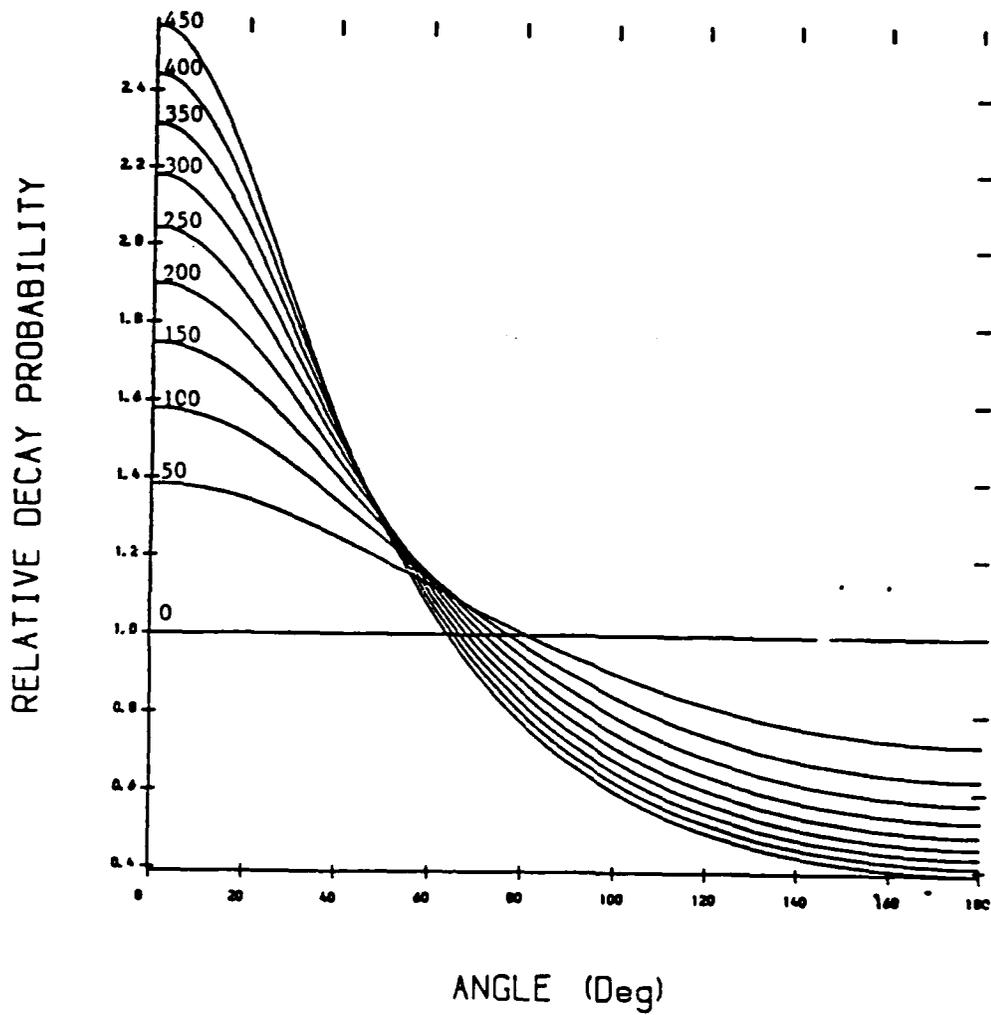


Figure 7. Relativistic correction factor for decay probability vs. angle. Various beam energies are shown.

The reply from McPherson Instruments was that with some development, such a spectrograph is feasible but expensive.

One may be puzzled by the fact that intensity distribution measurements have very poor resolution in our system, while Doppler shift measurements, also a local quantity, have a resolution of 2.8 μ rad. Intensity distribution determination requires by its nature the sampling of a very small volume, while the McPherson spectrograph can sample a relatively large volume. Thus, a decay probability of an $H^*(2p)$ of 0.1 in the volume sampled by the spectrograph can be achieved. Instrumental loss reduces the signal by a factor of 1.2×10^{-4} and a comparable reduction in signal is due to the solid angle. The relativistic correction factor of 0.65 further reduces the signal. Thus from 2.8×10^{10} Lyman-alpha photons per pulse, the spectrograph can detect about 12.

VI. CONCLUSION

It seems quite possible to neutralize a fast H^- beam using a short wavelength pulsed laser to excite the shape resonance. The laser intensity available will be enough to neutralize most of the ions. About half the neutral atoms will be in the 2p state which decays spontaneously to the 1s state with the emission of light, and about 13% will be formed in the 2s state which is metastable. Beam orientation can be determined from a straightforward measurement of the total fluorescence intensity of the Lyman-alpha radiation through the dependence of the shape resonance on angle. But this measurement is limited to a resolution of 40 μ rad. Nevertheless, this is by far the easiest and the simplest method.

Minute Doppler shifts $\Delta\lambda/\lambda \sim 10^{-6}$ of the Lyman-alpha radiation can be measured with a spectrograph to determine angular changes as small as 2.8 μ rad. This method is the most expensive, and it may not be applicable to beams that are more dilute than that of NBTf.

The use of photodetached H^- ions as a source of either $H^*(2s)$ or $H^*(3p)$ for schemes already proposed is very attractive. In the first case, if hot cathode e- beam drivers for ArF lasers are developed, $H^*(2s)$ atoms can be provided in a quantity comparable to that produced in a gas cell, without any of its drawbacks. In the latter case, no other satisfactory source of $H^*(3p)$ has been identified. This method can produce $H^*(3p)$ atoms a factor of 34 greater than a combination of a gas cell for 2s and an auxiliary laser to excite 2s-3p.

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