CRITERIA FOR THE PRODUCTION OF EXCITED ATOM BEAMS BY PHOTO-EXCITATION

by

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A B S T R A C T

Photo-excitation of hydrogen atoms from levels of low principal quantum number 'n' to levels susceptible to Lorentz ionization (n = 8 to 14) is considered for atoms in a neutral beam such as is used for injection into magnetic traps. The power requirement of a laser capable of increasing appreciably the number of atoms in the levels n = 8 to 14 is determined by the angular divergence, velocity straggling and diameter of cross-section of the beam, and the closeness to which the laser wavelength must match a hydrogen line is determined by the Doppler shifts resulting from the high velocity of the beam.

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INTRODUCTION

The maximum plasma density attainable in magnetic mirror containment devices stabilised by Ioffe conductors (such as Phoenix II) is determined by the balance between gain and loss processes. The dominant loss process is neutralisation of positive ions by charge transfer with atoms of the background gas, and the gain results from Lorentz ionization of hydrogen atoms injected into the mirror in the form of a fast neutral atom beam. Typical magnetic fields and beam velocities are such that only states of principal quantum number ~ 8 to ~ 14 undergo the Lorentz ionization process. A neutral atom beam is normally obtained by directing fast molecular ions through a region of high gas or vapour pressure but only a small fraction (about 0.01%) of the beam atoms emerge in the levels 8 to 14, the majority being in lower levels. Excitation from these lower levels could increase the useful beam by a large factor and it is of interest to consider the use of lasers for this purpose.

Table I gives the wavelengths (in vacuo) corresponding to s - p transitions between levels $n = 2$ to 4 and $n = 8$ to 14; the accuracy to which a useful laser wavelength must match these values is shown below to be about 1%. (Wavelengths for excitation from the ground level are not listed since the maximum useful wavelength in this case is only 926 Å).

TABLE I

WAVELENGTHS IN Å (COLUMNS HEADED 2s, 3s) OR IN μ (COLUMN HEADED 4s) CORRESPONDING TO TRANSITIONS IN HYDROGEN

	2s	3s	4s
8p	3890	9549	1.945
9p	3836	9232	1.818
10p	3799	9017	1.737
11p	3772	8865	1.681
12p	3751	8753	1.641
13p	3735	8667	1.611
14p	3723	8601	1.588

The mean life-times of the s states of the levels 2 to 4 are sufficiently long that, for beam energies of tens of kilovolts, only a very small fraction decay within a path length of (say) 10 cm following the neutraliser. The effect of the $v \wedge B_{EARTH}$ field reduces the mean life of the 2s level from its field-free value of about 1/8th second to 4×10^{-4} sec (at 25 keV) but this still corresponds to an adequate mean path of 10^5 cm.

PROBABILITY OF PHOTO-EXCITATION

For an atom in the path of a light beam in which the photon flux is $N(\varepsilon)$ photons cm^{-2} sec^{-1} eV^{-1}, the probability per sec, T, for excitation is given by

$$T = \int_0^\infty N(\varepsilon)\, \sigma(\varepsilon)\, d\varepsilon$$

where $\sigma(\varepsilon)$ is the effective cross section for absorption of a photon of energy ε, and is given by

$$\sigma(\varepsilon) = \frac{\pi}{2} \cdot \lambda\!\!\!^{-2} \cdot \frac{2b+1}{2a+1} \cdot \frac{\Gamma\, \Gamma_\gamma}{(\varepsilon - E_R)^2 + \frac{\Gamma^2}{4}}$$

where

Γ = total width of upper level plus total width of lower level

Γ_γ = partial width of upper level for radiative transitions to lower level

$\lambda\!\!\!^{-}$ = reduced wavelength

$2b + 1$ = statistical weight of upper level

$2a + 1$ = statistical weight of lower level

E_R = energy separation of levels

If $N(\varepsilon)$ varies only slowly over an energy interval about E_R much greater than Γ, then the integration may be carried out to give

$$T = N \left(\frac{\lambda}{2}\right)^2 \frac{2b+1}{2a+1}\, \Gamma_\gamma \qquad \ldots (1)$$

in which a consistent set of units is $T(sec^{-1})$, $N(cm^{-2}\ sec^{-1}\ eV^{-1})$, $\lambda(cm)$ and $\Gamma_\gamma(eV)$.

LASER EXCITATION

The photon flux per unit energy interval N depends not only on the power, band width and geometry of the laser beam but also on the angular spread and velocity straggling of the atomic beam and on the angle between the laser and the atomic beam. A discussion of the influence of these factors is given below and shows that an important case is that in which the two beams intersect at right angles, when velocity straggling may be neglected (the transverse Doppler effect is much smaller than other factors considered below). In this case the energy interval $\Delta\varepsilon$ over which we must consider the laser power to be spread is given by

$$\frac{\Delta\varepsilon}{\varepsilon} = 2\, \frac{v}{c}\, \Delta\theta$$

where v is the particle beam velocity and $\pm\Delta\theta$ is the angular spread (assumed uniform for simplicity), in the plane containing the two beams, of the atoms' velocity vectors.

If the laser power Q eV sec^{-1} is distributed over a rectangular area $w\ell$ cm^2 where ℓ is the dimension of each beam in a direction perpendicular to the plane of the beam and w is the width of the laser beam, then we can write for N

$$N = \frac{Q}{\varepsilon} \cdot \frac{1}{w\ell} \cdot \frac{c}{2\varepsilon v \Delta\theta} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ eV}^{-1}$$

Substituting this in (1) and multiplying both sides by the time w/v spent by each atom in the laser beam gives for the probability of excitation per atom P.

$$P = \frac{2b+1}{2a+1} \cdot \Gamma_\gamma \cdot \frac{c^3 h^2 Q}{8\ell\varepsilon^4 v^2 \Delta\theta} \qquad \ldots (2)$$

To obtain some appreciation of the magnitudes involved in equation (2) we apply it to the 3s - 11p transition and to a 25 keV beam of identical geometry to that used in the cross section experiments[1]. The factor $\frac{2b+1}{2a+1} \cdot \Gamma_\gamma$ can be obtained from the tabulation of radial integrals by Green et. al[2]; for the 3s - 11p transition it has the value 3.1×10^{-10} eV. Substituting into equation (2) the values

$\varepsilon = 1.40$ eV

$\theta = 6.3 \times 10^{-4}$ radians

$\ell = 2.5 \times 10^{-2}$ cm

$v = 2.0 \times 10^{8}$ cm/sec

$Q = 4.5 \times 10^{8}$ photons sec^{-1} (1 watt)

results in a figure of 4% for the probability of excitation per atom. (For the 2s - 11p transition this probability is less by a factor of 10).

The probability calculated above is of course a mean value averaged over all the atoms in the particle beam. However, the variation in the probability is over a range of 7 orders of magnitude, and since the average probability obtained is 4% this must mean that probabilities considerably in excess of unity are contributing to this average value. For the calculation to apply it is necessary to focus the laser beam so that its angular spread in the direction of the H^0 beam velocity is equal to that of the H^0 beam itself. The probability of excitation is then approximately the same for each atom in the beam and is equal to the mean probability calculated above.

In more detail, the finite angular spreads of the two beams results in any single atom experiencing a monochromatic beam of N_{TOTAL} photons sec^{-1} whose frequency changes steadily as the atom traverses the laser beam. The total probability of absorption $P(T) = \int_0^T \sigma(\varepsilon) N_{TOTAL}\, dt$ and $\varepsilon = \varepsilon(t)$. For any atom in H^0 beam,

$$\varepsilon = \varepsilon_0 - B\frac{\hbar\Delta\omega}{2} + \hbar\Delta\omega\frac{t}{T}$$

where $0 < B < 1$

$$d\varepsilon = \frac{\hbar\Delta\omega}{T}\,dt$$

and

$$P(T) = T\int_{-\infty}^{+\infty} \sigma(\varepsilon)\,\frac{N_{TOTAL}}{\hbar\Delta\omega}\,d\varepsilon$$

where the limits are set at $\pm\infty$ since $\hbar\Delta\omega \gg \Gamma$.

It is most probable that in practice some intermediate angle of intersection φ between the beams would be chosen in order to accomplish tuning of the Doppler shifted laser wavelength to the transition. For such a case

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{\text{velocity straggling}} = \frac{\Delta v \cdot \cos\varphi}{c}$$

$$\left(\frac{\Delta\lambda}{\lambda}\right)_{\text{angular spread}} = \frac{v\ \Delta\theta\ \sin\varphi}{c}$$

It is clear that velocity straggling will limit the sharpness of tuning at small angles of intersection whilst at large angles the limit will be set by the angular spread of the beam. Assuming that the fractional velocity straggling $\frac{\Delta v}{v}$ is 10^{-3} and using the same value for $\Delta\theta$ as above gives for the angle φ', at which the velocity straggling effect has become as large as the effect of angular spread at 90°, the value 50°. So a range of $\pm 40^{\circ}$ about the perpendicular is available for tuning without loss in excitation probability and this range corresponds to about $\pm$ ½% in λ.

The excitation of a large fraction of the atoms in the Phoenix injection beam is much more difficult to achieve because of the larger angular spread, velocity straggling and lateral dimensions of the beam. On emergence from the neutraliser the beam diameter is about 10 cm and its angular divergence $\pm 2^{\circ}$; comparison with the above shows that for otherwise identical conditions the probability of excitation per atom is reduced to the value 2×10^{-6}. The provision of a laser wavelength permitting small angles of intersection could not increase this by more than a factor of about 4 since the fractional velocity straggling of the beam is large, of order 10^{-2}. To achieve a probability of excitation of 1% would thus require a total laser light power of about 5 kilowatts. One could attempt to use many lasers with arrangements for producing many traverses of each light beam across the atomic beam, or utilise the internal laser beam, (only a tiny fraction of the light is absorbed by the atomic beam), but to effect a sufficiently large improvement seems difficult, even assuming a laser of suitable wavelength and (continuous) power of order 1 watt were available.

CONVENTIONAL LIGHT SOURCES

We now consider the use of conventional light sources and compare these with the laser. The conventional source cannot do better than to simulate the effect of passing the atomic beam through a uniform temperature enclosure with walls at some effective temperature which produces the same photon density in the wavelength region of interest as does the source itself. If this photon density is $N'_B(\varepsilon)$ photons cm^{-3} eV^{-1} then the probability per sec T of photon absorption by an atom is

$$T_B = \int_{-\infty}^{+\infty} \frac{c}{4} \cdot N'_B(\varepsilon)\, 4\sigma(\varepsilon)\, d\varepsilon$$

$$= N'_B(\varepsilon)\, c \int_{-\infty}^{+\infty} \sigma(\varepsilon)\, d\varepsilon$$

assuming $N'_B(\varepsilon)$ does not vary rapidly within an interval about E_R much greater than Γ. Comparing this with the equivalent expression in the case of the laser

$$T_L = N'_L(\varepsilon)\, c \int_{-\infty}^{+\infty} \sigma(\varepsilon)\, d\varepsilon$$

(where the prime indicates photon density) we see that the ratio of probabilities per unit time is just $N'_L(\varepsilon)/N'_B(\varepsilon)$ and if t_L, t_B are the times for which the H^O atoms remain in the laser beam and temperature enclosure respectively, the ratio of probabilities of excitation per atom is

$$\frac{P_L}{P_B} = \frac{N'_L(\varepsilon)\, t_L}{N'_B(\varepsilon)\, t_B}$$

Obtaining explicit forms for each case results in

$$\frac{P_L}{P_B} = 2.3 \times 10^5 \frac{Q(\text{watts})}{v\, \ell w \Delta\theta} \cdot \frac{e^{\varepsilon/kT}-1}{\varepsilon^4}$$

in which ε is in eV, $\Delta\theta$ in radians, v in cm sec^{-1}, and ℓ, w in cm; ℓ is the extent of the temperature enclosure in the direction of motion of the atomic beam. Applying this to the two beams discussed above gives for $\ell = 1$ cm

Small experimental beam $\quad \frac{P_L}{P_B} = 65\, Q(\text{watts})\, \frac{e^{\varepsilon/kT}-1}{\varepsilon^4}$.

Phoenix injection beam $\quad \frac{P_L}{P_B} = 3 \times 10^{-3}\, Q(\text{watts})\, \frac{e^{\varepsilon/kt}-1}{\varepsilon^4}$

If we consider the transition 3s - 11p and a temperature of 10^4 °K then the ε - dependent factor is 1.06. The parameter Q represents the total effective laser power in the case of many lasers or multiple reflections.

Table II gives the probability of excitation per atom in a 1 cm path length at 25 keV for 1s, 2s, 3s, 4s - 11p transitions and for effective temperatures 10^4, 3×10^4 and 6×10^4 °K. No suitable source of effective temperature greater than 10^4 °K is at present known to the author. Values for the probability of excitation per atom in the laser case can be obtained from table II, with the aid of the above equations.

TABLE II

PROBABILITY OF EXCITATION, PER ATOM IN THE INITIAL STATE, IN A 1 cm PATH AT 25 keV

Transition	Temp. °K	Probability of excitation per atom in initial state
1s → 11p	10^4	7.4×10^{-9}
	3×10^4	$.024 \times 10^{-2}$
	6×10^4	$.33 \times 10^{-2}$
2s → 11p	10^4	$.015 \times 10^{-2}$
	3×10^4	$.25 \times 10^{-2}$
	6×10^4	$.73 \times 10^{-2}$
3s → 11p	10^4	$.055 \times 10^{-2}$
	3×10^4	$.31 \times 10^{-2}$
	6×10^4	$.72 \times 10^{-2}$
4s → 11p	10^4	$.075 \times 10^{-2}$
	3×10^4	$.31 \times 10^{-2}$
	6×10^4	$.66 \times 10^{-2}$

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