Characteristics of a UF₆-H₂/HF nuclear-pumped laser

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Nuclear pumped lasers are characterized by high-threshold neutron fluxes and low gain. This is due primarily to the fact that the fissile gas, which has the largest partial pressure and hence has the largest fraction of fission energy deposited in it, is not the lasing species. The closer the fissile gas can be coupled to the actual lasing process, the more efficient the laser will be. In this paper, a model for a potential new nuclear-pumped HF laser is presented. Using a $^{235}\text{UF}_6$-H₂ gas mixture, a peak gain of about 50%/m and a threshold neutron flux of $<10^{14}/\text{cm}^2\cdot\text{s}$ are predicted. Recommendations are made concerning optimum use of the new system.

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I. INTRODUCTION

One of the major problems of scaling conventional electric discharge, e-beam, or chemical lasers to large dimensions is uniformly depositing energy throughout the active volume. Nuclear-pumped lasers (NPL) provide a potential solution to this problem. A nuclear-pumped laser converts the kinetic energy of fission fragments (FF) produced by fission reactions into electromagnetic energy. Since the mean free path of thermal neutrons through fissile gas mixtures can be many meters long, a large volume of gas can be uniformly pumped.

There have been two successful techniques for achieving laser action with nuclear pumping. With the first method, fissile material is contained in a coating or foil which lines the inside of the laser tube. With a boron-impregnated foil, the $^{1}n(n^{10}\text{B}, \alpha)^{7}\text{Li}$ reaction has produced laser action in mercury, $^{1}$ nitrogen, $^{2}$ and carbon. $^{3}$ With foils containing uranium, the more energetic $^{1}n(^{235}\text{U}, FF)^{2}$ FF reaction has produced laser action in carbon monoxide$^{4}$ and xenon. $^{5}$ Because the source of fission fragments is external to the gas mixture, as the tube radius or gas pressure become large, the fission energy is no longer deposited uniformly. $^{6}$ The second technique uses a fissile gas as the source of fission fragments and therefore is not subject to the same limitations. The $^{1}\text{He}(n, p)^{1}\text{H}$ reaction has produced laser action or optical gain in oxygen, $^{7}$ argon, $^{8}$ krypton, $^{9}$ and xenon. $^{10}$ The source of neutrons for either method is a pulsed nuclear reactor having a peak flux of $10^{14}$–$10^{17}$ neutrons/cm²·s.

In present nuclear-pumped lasers, the source of fission fragments is not the lasing gas. The most direct participant in the lasing process that the fissile gas has had is in systems similar to the $^{1}\text{He}$-Ar NPL. In this system, argon is pumped by charge-exchange collisions with molecular helium ions. $^{10}$ The fissile gas in a volumetrically pumped laser usually has the largest partial pressure, and therefore most of the fission energy is deposited in that gas. Therefore, if the number of steps required to transfer the fission energy from the fissile gas to the lasing gas can be reduced, the laser will be more efficient.

II. THE MODEL

Uranium hexafluoride ($\text{UF}_6$) and molecular hydrogen ($\text{H}_2$) flow through a laser tube. The tube is either part of a nuclear reactor or placed in the vicinity of a nuclear reactor capable of producing neutron fluxes of $10^{12}$–$10^{17}$ neutrons/cm²·s. When the reactor is pulsed, high-energy neutrons are produced and subsequently moderated to thermal energies. The fission reaction

$$n + ^{235}\text{UF}_6 \rightarrow 2\text{FF}$$

(1)

liberates 207 MeV of energy. Most of this energy appears as kinetic energy in a light fission fragment (98 MeV) and a heavy (67 MeV) fission fragment. While slowing down, the fission fragments deposit their energy in the gas, causing ionizations, excitations, and dissociations. Fluorine atoms which are dissociated from the UF₆ react with the hydrogen, creating nonequilibrium hydrogen fluoride:

$$\text{F} + \text{H} \rightarrow \text{H} + \text{HF}(v), \quad v = 1, 2, 3.$$  (2)

The first three vibrational levels of HF are populated in the ratio 1:3:4:1.7, $^{11}$ creating an inversion and hence optical gain.

The following species are considered:
uranium hexafluoride $^{235}\text{UF}_6$, $^{238}\text{UF}_6$
hydrogen H, H
fluorine F, F
hydrogen fluoride HF(ν)
neutrons n

gas temperature T_g.

The manner in which fission energy is deposited in the gas is described using the treatment by Wilson and DeYoung.12
The energy deposited at a distance r from the centerline of a tube of radius b by fission fragment i in gas component j is

\[ E'_j(r) = \frac{v_i}{l} \frac{E_i}{\varphi} \left[ 1 + \frac{R_i^{(i)}(\theta_k)}{R_j^{(i)}} \cos \left( \theta_i^{(i)}(\theta_k) \right) \right] - \left[ 1 - \left( \frac{R_i^{(i)}(\theta_k)}{R_j^{(i)}} \right)^{1/2} \right] \frac{1}{l}, \]  

(3)

where \( \theta_k = \frac{k(1 - 1)}{2} \), \( E_i^{(i)} \) is the initial energy of the fission fragment, i is the neutron mean free path, and \( \varphi \) is the thermal neutron flux. The neutron mean free path is given by \( l = 0.237(T_g/P_{UF}) \) cm, where \( P_{UF} \) is the 235UF pressure in atmospheres and the gas temperature is in K.13

The range of fission fragment i in the gas mixture, \( R_j^{(i)} \), is given by

\[ \frac{1}{R_j^{(i)}} = \sum_{j} \frac{n_j}{R_j^{(i)}}, \]  

(4)

where \( R_j^{(i)} \) is the range of fission fragment i per molecule/cm^3 of gas j, and \( n_j \) is the gas density. In Eq. (3)

\[ R_i^{(i)}(\theta) = (b^2 - r^2 \sin^2 \theta)^{1/2} - r \cot \theta. \]  

(5)

where \( \beta_j \) is the partial pressure of gas j. Of the fission fragment energy deposited in gas j, a fraction \( \beta_j \) results in dissociations. Therefore, the rate of production of F atoms due to nuclear pumping is

\[ \frac{\partial[F]}{\partial t} = \sum_j \frac{E_j^{(i)}R_j^{(i)}}{\gamma_i}, \]  

(7)

where \( \gamma_i \) is the average bond energy of an F atom in UF_n \( \gamma_i \approx 124 \) kcal/mole.14

The time rate of change of HF(ν = 1) is given by

\[ \frac{dN_i}{dt} = (M_kM_i - N_iM_{i+1}) + (M_{i+1}M_i - N_{i+1}M_i + 1) 

- \sum_{j} \left[ N_j - \frac{N_{i-1}N_i}{kT_k} \right. \left. - \frac{(E_{i-1} - E_i)(E_i - E_{i+1})}{kT_k} \right] R_i^{(i)}, \]  

(8)

where \( N_i \) is the density of HF in vibrational level i; \( E_i \) is the energy of vibrational level i, \( M_k \) is the density of species k, and \( M_{i+1} \) is the density of species k in vibrational level i. The first term on the right-hand side of Eq. (8) describes the pumping reaction (2) having rate constant \( r_{i-1} \), and its reverse reaction with rate constant \( r_{i+1} \). The second term describes the production of \( N_i \), by the reaction

\[ F_2 + H \rightarrow HF(\nu) + F, \quad \nu = 0, 1, 2, \ldots, 8. \]  

(9)

Reaction (9) makes a small contribution to the HF density because of the small density of F_2. This situation may be artificial. It was assumed that only F atoms are produced as products in a UF_n dissociation. This assumption is consistent with the observation that laser emission occurs only for \( v < 3 \) in HF lasers using a UF_n-H_2 gas mixture and flashlamps to dissociate the UF_n.15,16 This suggests that very few F_2 molecules are produced in the dissociations. If a significant amount of F_2 results from FF bombardment of UF_n, then reaction (9) will be important.

The third and fourth terms of Eq. (8) describe the time rate of change of \( N_i \) due to VV collisions with other HF molecules. The rate constant \( k_{VV} \) is for collisions where

\[ N_i + N_j \rightarrow N_{i+1} + N_{j-1}. \]  

(10)

It will be shown that this term plays a major role in quenching gain and dictates the requirement that the neutron pulse rise rapidly for maximum gain.

The fifth and sixth terms of Eq. (8) describe VV reactions of \( N_i \) with species \( M_{i+1} \) with rate constant \( r_{i+1}^{VV} \). The only species besides HF considered for vibrational exchange is H_2. The vibrational levels of H_2 were taken to be in thermal equilibrium with the gas temperature.

Vibrational-translational reactions where

\[ N_i + M_k \rightarrow N_{i-1} + M_k \]  

(11)

with rate constant \( r_{i-1}^{VT} \) are described by the seventh and eighth terms of Eq. (8). Because high pressures are required for fission energy to be deposited efficiently, VV reactions...
are a major quenching mechanism. The next four terms of Eq. (8) describe the change in $N_r$ due to fundamental and first overtone spontaneous emission, with rates $A_{hl}$ and $A_{l'}$. The next term of Eq. (8) describes the loss of $N_r$ due to diffusion with rate constant $D$ and diffusion length $A$. This term makes a small contribution due to the high operating pressure. The last term, the change in density due to gas heating, does not appear if the number density instead of the pressure is kept constant.

The time rates of change in the densities of $H_2$ and $H$ are given by

$$\frac{dM_{H_2}}{dt} = -\sum_i \frac{\gamma_{H_2}}{\gamma_H} \left( M_{H_2} r_i + M_{H_2} r_i \right) \right)$$

$$+ (M_{H_2} M_{H_2}) - (M_{H_2} M_{H_2})$$

$$+ (M_{H_2} M_{H_2}) - (M_{H_2} M_{H_2})$$

$$- \frac{D_{H_2}}{\gamma_H} \frac{dM_{H_2}}{dt}$$

$$- \gamma_H \frac{dM_{H_2}}{dt}$$

$$- \frac{D_{H_2}}{\gamma_H} \frac{dM_{H_2}}{dt}$$

$$\frac{dM_H}{dt} = \sum_i \frac{2 \gamma_{H_2}}{\gamma_H} \left( M_{H_2} r_i - M_{H_2} r_i \right)$$

$$+ (M_{H_2} M_{H_2}) - (M_{H_2} M_{H_2})$$

$$+ (M_{H_2} M_{H_2}) - (M_{H_2} M_{H_2})$$

$$- \frac{D_{H_2}}{\gamma_H} \frac{dM_{H_2}}{dt}$$

$$- \gamma_H \frac{dM_{H_2}}{dt}$$

$$- \frac{D_{H_2}}{\gamma_H} \frac{dM_{H_2}}{dt}$$

The first terms of Eqs. (12) and (13) describe the energy deposited by fission fragments and are analogous to reaction (7) for fluorne. The second terms describe the pumping reactions for $N_r$. The next three terms are for the dissociation and reassociation reactions

$$H_2 + H_2 \rightarrow 2H_2 + H_2$$

$$H_2 + M \rightarrow 2H + M$$

$$H_2 + H_2 \rightarrow 3H_2$$

where $M$ is any third body except $H_2$ or $H$. These reactions, as well as the last terms describing diffusion and thermal expansion, make small contributions compared to the first two terms and are included for completeness only. The expressions for $F_2$ and $F$ are analogous to Eqs. (12) and (13) where reaction (7) is included in the expression for $F$. Since $N_{F2}$, $N_{F2}$, and $N_{UF_2}$, any fission energy deposited in $F_2$ was ignored.

Due to the high pressure of $UF_6$, the densities of $^{235}UF_6$ and $^{238}UF_6$ remain nearly constant. Any dissociation products of $UF_6$ other than $F_2$ were ignored. With this assumption, changes in the $UF_6$ densities are simply

$$\frac{dM_{UF_6}}{dt} = - \sum_i \gamma_{UF_6} \left( M_{UF_6} r_i - M_{UF_6} r_i \right)$$

$$+ (M_{UF_6} M_{UF_6}) - (M_{UF_6} M_{UF_6})$$

$$+ (M_{UF_6} M_{UF_6}) - (M_{UF_6} M_{UF_6})$$

$$- \frac{D_{UF_6}}{\gamma_H} \frac{dM_{UF_6}}{dt}$$

$$- \gamma_H \frac{dM_{UF_6}}{dt}$$

$$- \frac{D_{UF_6}}{\gamma_H} \frac{dM_{UF_6}}{dt}$$

$$\frac{dM_{UF_6}}{dt} = - \sum_i \gamma_{UF_6} \left( M_{UF_6} r_i - M_{UF_6} r_i \right)$$

$$+ (M_{UF_6} M_{UF_6}) - (M_{UF_6} M_{UF_6})$$

$$+ (M_{UF_6} M_{UF_6}) - (M_{UF_6} M_{UF_6})$$

$$- \frac{D_{UF_6}}{\gamma_H} \frac{dM_{UF_6}}{dt}$$

$$- \gamma_H \frac{dM_{UF_6}}{dt}$$

$$- \frac{D_{UF_6}}{\gamma_H} \frac{dM_{UF_6}}{dt}$$

where $\sigma_f$ is the thermal fission cross section ($\sigma_f = 577 \times 10^{-24} \text{cm}^2$) and $\alpha$ is the enrichment. Additional reactions such as

$$H + UF_6 \rightarrow HF + UF_5, \quad \Delta H \approx -46 \text{ kcal/mole}, \quad (17)$$

$$H_2 + UF_6 \rightarrow 2HF + UF_4. \quad (18)$$

were ignored. The exothermicity of reaction (17) is sufficient to populate the fourth vibrational level of HF and therefore may also be a pumping reaction. It was assumed that fission energy which does not cause dissociations heats the gas mixture. This can be considered a worst-case analysis as much of this energy causes ionizations and excitations. Nevertheless, the change in gas temperature turns out to be small during the period of positive gain. The time rate of change in gas temperature is

$$\frac{dT_g}{dt} = \frac{1}{(\Sigma_{k} M_k \rho_k)} \left( -h \alpha (T_g - T_w) \right)$$

$$+ \sum_i \gamma_{UF_6} \left( 1 - \beta_i \right) + \sum_i (M_{UF_6} r_i \Delta \varepsilon)$$

$$\text{where} h = \text{the heat transfer coefficient}, A_1 = \text{the surface area of the tube}, V = \text{the volume of the tube}, T_g = \text{the wall temperature}. \text{The terms of Eq. (19) describe conduction of heat to the wall, energy deposited by fission fragments, and energy (\Delta \varepsilon) transferred to the gas during VT collisions. The heat capacity of the gas component k is \rho_k.}$$

The range of fission fragments in $UF_6$ and $H_2$ is listed in Table I. The rate constants for the pumping reactions and their inverses, as well as the VV rates, and VT rates for $HF, H_2, F_2$, and $F$ were taken from the compilation by Cohen. The VT rate for $UF_6$ was estimated to be the same as for $SF_6$. Spontaneous emission coefficients for HF($\nu$) were taken from the work of Herbelin and Emanuel. The thermodynamic properties of $UF_6$ can be found in Refs. 21 and 22. The remaining heat capacities were taken from the JANAF tables.

Gain for the vibrational rotational transition $N_{v'\rightarrow v'} - N_{v' \rightarrow v'}$ can be calculated from the expression

$$\gamma_{v' \rightarrow v'} = \frac{A_{11}}{2 \pi} A_{11} g(v) g(v) \left( N_{v' \rightarrow v'} - N_{v' \rightarrow v'} \right) \frac{g(v)}{g(v)}$$

$$\text{where} g(v) = \text{the line-shape function and} g(v) = \text{the degeneracy of the level. At each time step, the maximum gain for a P-branch transition is calculated. The values of gain for a particular vibrational transition discussed in Sec. III therefore do not necessarily refer to the same rotational line.}$$

| TABLE I. Range of fission fragments in $UF_6$ and $H_2$. (The range is obtained by dividing the value in the table by the gas density.) |
|---------------------------------|-----------------|-----------------|
| Fission fragment | Range in $UF_6$ | Range in $H_2$ |
| (Ref. 12) | (Ref. 26) | (Ref. 26) |
| Light | $1.18 \times 10^{19}/\text{cm}^2$ | $1.23 \times 10^{19}/\text{cm}^2$ |
| Heavy | $1.05 \times 10^{19}/\text{cm}^2$ | $1.00 \times 10^{19}/\text{cm}^2$ |


M. J. Kushner 2423
In previous models of nuclear-pumped lasers and plasmas, a constant neutron flux was assumed.\textsuperscript{10,25} Nuclear-pumped lasers usually operate as long as the neutron flux is above threshold so that a quasi-steady-state assumption is justified. UF\textsubscript{6}-H\textsubscript{2} system proposed here does not display this behavior and on the contrary is a sensitive function of the shape of the neutron pulse. Pulsed nuclear reactors which have been used for NPL have neutron pulses which are roughly Gaussian in shape with a FWHM from 60\,\mu s to 15 ms.\textsuperscript{1-4} Therefore, a Gaussian was assumed for the time dependence of the neutron flux. The FWHM and peak flux were kept as free parameters.

For otherwise constant conditions, the rate of formation of HF is proportional to $\alpha \beta \varphi$ where $\alpha$ is the UF\textsubscript{6} enrichment, $\beta$ is the fraction of the fission energy deposited which results in dissociations, and $\varphi$ is the time-dependent neutron flux. For the range of conditions considered here, doubling the flux and halving the enrichment causes a negligible change in the results. Similarly, doubling the flux while halving $\beta$ changes the results little. The actual value of $\beta$ is at present unknown. Therefore, in the discussion which follows, the neutron flux is referred to as the "flux factor," $\varphi = \alpha \beta \varphi$. $\varphi$ has the same units as the actual flux $\varphi$, but gives a more realistic indication as to the pumping power of the neutron flux.

III. RESULTS AND DISCUSSION

Typical results showing gain and densities at the centerline of a tube for a neutron pulse in a UF\textsubscript{6}-H\textsubscript{2} mixture are shown in Fig. 1. The total pressure is 0.4 atm, the initial gas temperature is 500°K, and the fraction of hydrogen is 1.3%. The neutron pulse has a FWHM of 60\,\mu s and the peak flux factor is $2 \times 10^{15}$ neutrons/cm\textsuperscript{2}\textsuperscript{s}. (The pressure and fraction of hydrogen yield maximum gain for the particular choice of peak flux factor and pulse width.) Note that peak gain occurs for the $v = 1 \rightarrow 0$ transition ($j = 3$) and has a value of about

![FIG. 1. Results for a neutron pulse in a UF\textsubscript{6}-H\textsubscript{2} gas mixture. The densities are per cm\textsuperscript{3}. The flux factor has units of neutrons/cm\textsuperscript{2}\textsuperscript{s}, and has a peak value of $2 \times 10^{15}$. The total pressure is 0.4 atm and the fraction of hydrogen is 1.3%.](image1)

![FIG. 2. Maximum gain and the time after the beginning of the neutron pulse that maximum gain occurs as a function of the width of the neutron pulse. The peak flux factor for each case is $2 \times 10^{15}$ neutrons/cm\textsuperscript{2}\textsuperscript{s}. The total pressure is 0.4 atm and the fraction of hydrogen is 1.3%. The quenching time is only a function of pressure. Hence, a more rapidly rising neutron pulse populates the upper levels more heavily before the quenching time passes. The efficiency, though, decreases as the width decreases.](image2)

![FIG. 3. Maximum gain and flux efficiency as a function of peak flux factor. The width of the neutron pulse is constant at 60\,\mu s. Total pressure is 0.4 atm and the fraction of H\textsubscript{2} is 1.3%. As the peak flux factor increases, the maximum gain increases, but the flux efficiency and length of time of positive gain decreases.](image3)
nism is UF₆-HF VT collisions. Since this quenching rate is constant, as the flux increases, gain increases. But when the density of ground state HF exceeds a few times 10¹²/cm³, the dominant quenching mechanism changes to VT and VV collisions with ground-state HF. As the flux increases, the rate of formation of excited HF increases, but the rate of formation of ground-state HF (and hence the quenching rate) increases even more rapidly. Eventually the quenching rate dominates and positive gain can no longer be sustained.

Note that during the neutron pulse, the maximum gain occurs at about 10 µs when the flux factor is only 2% of its peak value. For a given pressure of UF₆, there is a quenching time, τ_q, which must pass before the density of ground-state HF becomes comparable to the upper levels. This time is on the order of the inverse of the quenching rate, τ_q ~ 5µs/P_{UF₆} at 500 °K where the UF₆ pressure is in atmospheres. Therefore, the larger the rate of rise of the neutron flux, the larger the density of excited HF is before this quenching time passes. Hence maximum gain will be proportional to the rate of rise of the neutron flux. Once τ_q has elapsed, the HF quenching rate is largest where the density of ground-state HF is the largest. Therefore, the length of time that gain is positive is inversely proportional to rate of pumping. This is illustrated in Fig. 2 where for a constant peak flux factor (Φ = 2×10¹⁵ neutrons/cm²s) the FWHM of the neutron pulse was varied. Note that as the pulse width decreases, the peak gain increases and the time at which the gain is maximum decreases. The efficiency with which the neutron flux is used also increases with decreasing pulse width. The ratio of the flux factor at the time of maximum gain to the flux factor at its peak value has been termed the flux efficiency. The flux efficiency increases from less than 1% with a FWHM of 30 µs to almost 10% with a FWHM of 200 µs.

26%/m. Maximum gain for the v = 2→1 transition is about 21%/m (η = 3). Gain is never positive for the v = 3→2 transition. At the beginning of the neutron pulse, there is no HF. As the flux rises, gain is initially largest on the 2→1 transition because of the branching ratio which favors the second vibrational level. Initially, the dominant quenching mecha-

![FIG. 4. Gain for the ν = 1→0 transition as a function of the time after the start of the neutron pulse and the peak flux factor for a pulse width of 60 µs. The conditions are the same as Fig. 3. As the peak flux factor decreases the HF-HF quenching rate decreases. Gain then is quenching primarily by UF₆ VT collisions. The length of time which gain is positive approaches the length of the neutron pulse.](image)

![FIG. 5. Maximum gain and the flux efficiency for constant number densities as a function of initial gas temperature. The reference conditions are the same as for Fig. 1. Since the HF-HF VV quenching rate is endothermic, gain and flux efficiency increase as the gas temperature decreases.](image)


M. J. Kushnern
When the neutron pulse width is held constant (60μs) and the peak flux factor is varied, similar results are obtained. Figure 3 shows maximum gain rising rapidly as the peak flux factor increases while the flux efficiency decreases. For a sufficiently small peak flux factor, the density of HF never becomes large so that the dominant quenching mechanism remains UF₆-HF VT collisions. Under these conditions, the gain is not abruptly quenched and the length of time which gain is positive approaches the length of the neutron pulse. (See Fig. 4.)

The threshold peak flux factor for an HF laser can be estimated from Fig. 3. The threshold pumping rate for a laser is that value at which gain for the photon flux equals losses. If the dominant loss mechanism is output coupling (cavity length ≈2m, output mirror reflectance ≈95%), then the threshold peak flux factor will be of the order of $5 \times 10^{12}$ neutrons/cm²s. For $\alpha = 1.0$ and $\beta = 0.1$, the threshold peak flux is less than $10^{14}$/cm²s. The threshold flux can be further reduced by shortening the pulse width or decreasing the gas temperature (see below). This threshold flux is lower than any value reported to date. (See Table II.) The maximum gain calculated is comparable to any reported to date. (See Table III.)

We have seen that as long as UF₆-HF VT collisions are the dominant quenching mechanism, gain is proportional to the time-dependent flux factor. When VV collisions between ground-state and excited HF become the dominant mechanism, gain is quickly quenched. Since these collisions are endothermic, reducing the gas temperature will decrease their importance. Figure 5 illustrates the temperature dependence of maximum gain for constant initial number densities. The reference conditions are the same as for Fig. 1. Note the maximum gain increases roughly linearly as the initial gas temperature is reduced, and that the flux efficiency increases sharply. For temperatures below about 300 °K, the UF₆ pressure exceeds the saturated vapor pressure of UF₆, and therefore sets a lower limit (for a given UF₆ density) on the initial gas temperature.

### Table II: Threshold thermal neutron fluxes for present nuclear-pumped lasers.

<table>
<thead>
<tr>
<th>Fission reaction</th>
<th>System</th>
<th>Threshold thermal neutron flux (cm/s)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}(n,p)^3\text{Li}$</td>
<td>He-CO₂</td>
<td>C</td>
<td>4×10¹⁴</td>
</tr>
<tr>
<td>$^3\text{He}(n,p)^3\text{Li}$</td>
<td>He-N₂</td>
<td>N</td>
<td>1×10¹⁵</td>
</tr>
<tr>
<td>$^3\text{He}(n,p)^3\text{H}$</td>
<td>He-Xe</td>
<td>Xe</td>
<td>4×10¹⁴</td>
</tr>
<tr>
<td>$^3\text{He}(n,p)^3\text{Li}$</td>
<td>He-Hg</td>
<td>Hg</td>
<td>10¹⁵</td>
</tr>
<tr>
<td>$^3\text{He}(n,p)^3\text{O}$</td>
<td>He-Ar</td>
<td>Ar</td>
<td>1.4×10¹⁶</td>
</tr>
</tbody>
</table>

For a given pressure, peak flux factor, and pulse width, there is an optimum fraction of H₂, which is around a few percent. Figure 6 shows the results of varying the fraction of H₂ for otherwise constant conditions. For values below optimum, the reaction which forms HF is limited by the small amount of H₂ present. As the fraction of H₂ is increased, more fission energy is deposited in the hydrogen instead of the UF₆. The rate of production of F decreases so that despite the abundance of H₂, the reaction rate for forming HF decreases (see Fig. 7). The length of time that gain is positive and the flux efficiency increases as the fraction of H₂ decreases.

The results discussed thus far have been for gain on the centerline of a tube whose radius is optimum. An optimum tube radius is one which exceeds the range of the fission fragments. Therefore, for a given pressure and gas composition there is a tube radius below which energy deposited on the centerline will decrease. Alternately, one can consider the annular region adjacent to the wall of the tube with a thickness equal to the range of the fragments as a region where energy is not uniformly distributed. For points interior to this annular region, the energy deposition is uniform.

Figure 8 shows maximum gain for the $\nu = 1 \rightarrow 0$ transition as a function of pressure and tube radius. The peak flux factor is $2 \times 10^{15}$/cm²s and the neutron pulse width is 60μs. The fraction of H₂ is 3%. Also shown in Fig. 8 is the maximum range of fission fragments for the gas mixture as a function of pressure. Note that the optimum pressure is around 0.35 atm, independent of the radius of the tube, but that the optimum gain decreases with decreasing radius as long as that radius is less than optimum. The precise value of the optimum pressure increase slightly with decreasing tube radius.

For pressures greater than about 0.3 atm, the vibrational-rotational transition is purely pressure broadened. There-
fore, for otherwise constant conditions, a decrease in pressure results in an increase in the maximum value of the line-shape function \( g(v) \) and hence gain is enhanced. Below about 0.3 atm, the transition to Doppler broadening begins, and the line-shape advantage gained by lowering the pressure is lost. Since the major quenching mechanism early during the neutron pulse is \( \text{UF}_6 - \text{VT} \) collisions, lowering the pressure increases the quenching time \( \tau_q \), and delays the time when HF collisions become dominant. This is illustrated in Fig. 9 where the time at which gain for the \( v = 1 \rightarrow 0 \) transition is maximum is plotted as a function of pressure and tube radius. If the pressure is increased, the energy deposited in the gas and hence the pumping rate increases. But the increase in the pumping rate is insufficient to offset the decrease in \( \tau_q \) and \( g(v) \).

For pressures below about 0.35 atm the advantage gained with respect to decreasing quenching rates by lowering the pressure is smaller than the decrease in fission energy deposited and the decrease in the reaction rate that produces HF. This results in a decrease in maximum gain. For sufficiently low pressure, the range of fission fragments exceeds the radius of the tube. The rate at which energy is deposited and hence maximum gain decrease sharply.

The results discussed above are a function of the peak flux factor and temperature. Increasing the peak flux factor increases the optimum gain and shifts the optimum pressure to a lower value. Decreasing the gas temperature decreases the Doppler width and decreases the pressure at which the transition to Doppler broadening is made. This results in a lower optimum pressure and higher optimum gain.

**IV. CONCLUDING REMARKS**

A model for a nuclear-pumped \( \text{UF}_6 - \text{H}_2 - \text{HF} \) laser has been presented. The results show that this system potentially has the lowest neutron flux threshold of any nuclear pumped system to date (less than \( 10^{14} \) neutrons/cm\(^2\) s), while the gain is comparable to any yet measured (greater than 50% m). The gain is a sensitive function of the rate at which the neutron pulse rises. Because the gain is rapidly quenched, the rate of rise of the neutron pulse is more important than its peak flux. Therefore, threshold fluxes may be as much as an order of magnitude less than suggested here if the flux can be made to rise fast enough. The threshold rate of rise of the neutron flux is on the order of \( 10^{11} - 10^{13} \) neutrons/cm\(^2\) s\(^2\). Optimum gain is obtained at the lowest temperature at which the optimum density is less than the saturation pressure of \( \text{UF}_6 \), and with a fraction of \( \text{H}_2 \) equal to a few percent.

Present nuclear-pumped lasers, as well as the system proposed here, have relatively low gain. The motivation for their development should be because energy can be deposited uniformly in a large volume. This characteristic makes them attractive as amplifiers instead of oscillators. Consider an HF nuclear-pumped amplifier 1 meter in diameter and a few meters long. The output of an oscillator with a spot 1 cm in diameter is expanded, passed through the amplifier, and then contracted to its original size. The increase in intensity that the spot experiences would be equivalent to passing through an amplifier at its original radius which is many kilometers long.

_Note added in proof:_ cw nuclear pumped lasing on the 6328-Å neon transition in a He-Ne system at 300 Torr has been recently reported [B.D. Carter, M.J. Rowe, and R.T. Schneider, Appl. Phys. Lett. 36, 115 (1980)]. The threshold neutron flux was measured at 2 \times 10\(^{11}\) neutrons/cm\(^2\) s sec.

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18Reaction (17) is analogous to the reaction $H + SF_4 \rightarrow HF + SF_3$, with rate constant $r = 3 \times 10^{-6} \text{cm}^3/(M \cdot \text{s})$. C. P. Fenimore and G. W. Jones, Combust. Flame 8, 231 (1964).