Fission fragment pumping of a neon plasma

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A method for calculating excitation and ionization rates in a plasma generated by the slowing of fission fragments in a gaseous medium (neon) is presented. The energy distribution of the fission fragments as they slow down, and the excitation and ionization of neon due to collisions with the fission fragments, are discussed. Effective W values for ionization and excitation of neon directly by the fission fragments of uranium (71.6 and 110 eV) are derived. The source function for electrons produced by direct ionization by the fission fragments is discussed and compared to that produced by an e beam. The source function of electrons produced by heavy ions has the lower average energy.

There is considerable interest in using fission fragment pumping to generate plasmas[1–3] for uses previously satisfied by electric discharges or e beam plasmas. Our interest is in the application of such pumping schemes to the excitation of gas lasers. To analyze and optimize pumping of gas lasers by this method, one must be able to quantify the manner in which the kinetic energy of the fission fragments is ultimately transferred to the upper laser level. This process involves collisions of the fission fragments (energetic heavy ions) with the gas which directly results in excitation and ionization and the generation of energetic secondary electrons which also excite the gas. The end result is a low-temperature plasma ($T_e \simeq 1$ eV). In this paper, we discuss the slowing of fragments from ^{235}U fission (see Table I) in a neon buffer gas, and the distribution of electrons generated by direct ionization of the gas by the fission fragments. This work is an extension of the formalism of Guyot, Miley, and Verdeyen,[3] who also studied the slowing of fission fragments in gases. In our work, we solve for the velocity distribution of the fission fragments and then use the integral cross sections of Gryzinski[4] for heavy particle-electron collisions to calculate the rate of ionization of the gas. We calculate the metastable excitation rate by integrating over the fission fragment distribution without using an *a priori* assumption as to the number of excitations per energy loss. This allows us to directly calculate the W value (energy/ion) for the fission fragments and the number of excitations per ionization.

Unlike discharges, there is no electric field in a fission fragment pumped plasma so the spectrum of electrons produced by ionization of the gas mixture by the fission fragments is the source of energy for the electron energy distribution (EED). The spectrum of electrons produced by the fission fragments will be noticeably different from the spectrum produced by an e beam, primarily due to the difference in the projectile masses. The resulting change in the EED will cause changes in electron impact excitation, recombination, and attachment rates, and therefore in the performance of the laser. Our approach for computing the spectrum of source electrons considers binary collisions between the fission fragments and the orbital electrons in the gas atoms.[4] With a large difference in mass, only a small fraction ($\simeq m/M$) of the fission fragment energy can be transferred to the electron, leading to a product electron source spectrum that is highly peaked at low energy. Due to the more favorable mass ratio, the spectrum produced in an e beam plasma will have a higher electron temperature (T_e). Therefore, one should expect a difference in the method of excitation of excimer lasers between fission fragment pumping and e beam pumping.

The method whereby the fission fragment velocity distribution and secondary electron energy spectrum are calculated will now be discussed. This formulation is only concerned with the electronic stopping power. The contribution due to the interaction of the fission fragment with the gas molecule as a whole is only important at energies lower than the electronic thresholds. This contribution results in gas heating and therefore does not add to the rate of electronic excitation or ionization.

The slowing of energetic ions is usually described by the stopping power, dE/dx. Finding it more convenient to work in terms of the velocity, we use the result of Srivastava and Mukherji[5] to obtain the stopping power in terms of the velocity, $S(V)$. For our range of parameters (see Table I)

$$S(V) = \frac{1}{M}\frac{dE}{dx} = \frac{2\pi N e^2}{M m_e}\left(\frac{q}{V}\right)^2 2f(Z_g) \times (3\chi^{-1/3} + \chi^{-1})\frac{V}{V_0}, \tag{1}$$

where N is the gas density, M is the ion mass, m_e is the electron mass, e is the elemental charge, V is the ion velocity, V_0 is the atomic unit of velocity (2.18×10^8 cm/s), q is the ion charge, and Z_g is the atomic number of the gas. We also have $\chi \equiv 2(q/e)(V_0/V) > 1$ and for $Z_g < 46$, $f(Z_g) = 0.28\,Z_g^{2/3}$.

As the ion slows down it gains electrons by charge exchange,[6] thereby reducing q. We use an empirical relation to give the equilibrium average charge as a function of the ion's velocity (see Fig. 5.11 of Ref. 6)

$$\bar{q} = \frac{1}{2}\frac{V}{V_0}Z_{\rm ion}^{0.45}\,e, \quad \rightarrow \chi(V,\bar{q}) = Z_{\rm ion}^{0.45}. \tag{2}$$

Using this equilibrium charge

$$S(V) = \frac{2\pi N e^4}{M m_e} \frac{1}{4} \left(\frac{Z_{\text{ion}}}{V_0}\right)^2 (0.56\, Z_g^{2/3})$$
$$\times (3 Z_{\text{ion}}^{-0.15} + Z_{\text{ion}}^{-0.45}) \frac{V}{V_0},$$
$$= h(Z_{\text{ion}}, Z_g)\, V. \quad (3)$$

The spatially averaged ion velocity distribution, $\overline{F}(V)$, is calculated next. The slowing of the ions, $S(V)$, is considered as a deceleration and the resulting Boltzmann equation is

$$V \frac{\partial F}{\partial x}(V,x) - S(V) \frac{\partial F}{\partial x}(V,x) = 0,$$
$$\rightarrow \frac{V}{S(V)} \frac{\partial F}{\partial x} = \frac{\partial F}{\partial V}, \quad (4)$$

where $F(V,x)$ is the distribution of fission fragments with velocity V at position x. Integrating over position for the full range of the ion, beyond which $F = 0$, and defining $H(V) = \int F(V,x)dx$ as the integrated velocity distribution, we have

$$\frac{-V}{S(V)} F(V, x=0) = \frac{\partial H(V)}{\partial V},$$
$$\rightarrow H(V) = \int_V^{V_{\max}} \frac{\phi(V)\, dV}{S(V)}, \quad (5)$$

where the initial flux, $\phi(V) = VF(V, x=0)$, and the initial velocity is $V_{\max}$.

To get the spatially averaged velocity distribution we divide by the full range, $R(V_{\max})$, and obtain $\overline{F}(V) = H(V)/R(V_{\max})$. The range is given by

$$R(V_{\max}) = \int_0^{V_{\max}} \frac{V\, dV}{S(V)} = \frac{V_{\max}}{h(Z_{\text{ion}}, Z_g)}, \quad (6)$$

where the last equality uses Eq. (3). Using Eq. (5) we finally get

$$\overline{F}(V) = \frac{1}{V_{\max}} \int_V^{V_{\max}} \frac{\phi(V)\, dV}{V}. \quad (7)$$

The next step is to use this distribution with the cross section for ionization of the gas by the ions to obtain the electron production rate.

Our description of the collisions between the ions and the neon atoms is based on the Gryzinski[4] cross sections for binary Coulomb collisions. Figure 1 shows the relevant cross sections. These cross sections are weighted by the effective ion charge at velocity V for the conditions in Table I, and assuming the six $1p$ electrons of neon interact with the ion. By using the cross section differential with respect to energy exchange, $\sigma(V, \Delta\epsilon)$, we get the spectrum of product (secondary) electrons,

$$\Psi(\epsilon) = N \int dV \overline{F}(V)\, V \sigma(V, \epsilon + u_i), \quad (8)$$

with u_i being the ionization potential and N the gas density. The integral cross section, $Q(V, u_i)$, gives the total ionization rate,

$$\nu_i = N \int dV \overline{F}(V)\, VQ(V, u_i). \quad (9)$$

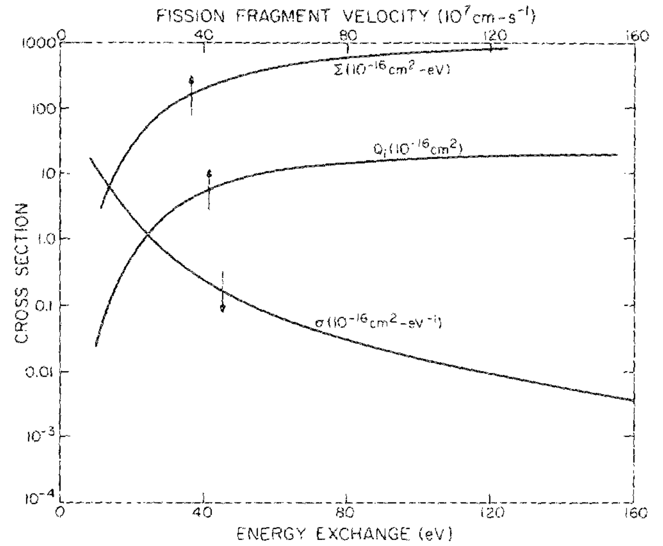

FIG. 1. Fission fragment collision cross sections in neon given by the Gryzinski formulation weighted by the effective charge $q(v)$. The differential cross section with respect to energy exchange $\sigma(V, \Delta\epsilon)$ is shown as a function of $\Delta\epsilon$ (in eV) at an ion velocity of $V^2 = 1$ MeV/amu, and the units are Å^2/eV. The integral cross section for ionization, $Q_i(V)$ (in Å^2) is plotted against V (in units of 10^7 cm/s), as is the stopping power cross section, $\Sigma(V)$ (in eV Å^2).

The stopping power cross section, $\Sigma(V, u_{\text{ex}})$, is used to obtain the rate of energy loss of the ions

$$\nu_\epsilon(u_{\text{ex}}) = N \int dV \overline{F}(V)\, V \Sigma(V, u_{\text{ex}}). \quad (10)$$

The metastable excitation rate is evaluated by dividing the rate of energy transfer to the excited states by the metastable threshold,

$$\nu_{\text{ex}} = [\nu_\epsilon(u_{\text{ex}}) - \nu_\epsilon(u_{\text{ion}})]/u_{\text{ex}}. \quad (11)$$

We now consider the slowing of U^{235} fragments in neon. We assume that the initial flux of fission fragments is a δ function at the velocity immediately after the fission event. We follow the convention of using a light and a heavy ion to represent the fission products (see Table I). As a check of our method, we perform an energy balance for the ion energy losses. With the ion deceleration proportional to its velocity we have [see Eq. (3)] $V(t) = V_{\max} e^{-ht}$. Using $V_{\min} = 0.1 V_{\max}$ as the lowest velocity that is important, the time needed to slow down, τ, is

$$\tau = \ln(V_{\max}/V_{\min})/h(Z_{\text{ion}}, Z_g)$$
$$= 2.2/h(Z_{\text{ion}}, Z_g). \quad (12)$$

Table II compares the energy loss rate coefficient, k_ϵ, calculated using the Gryzinski stopping power cross section

TABLE I. Characteristics of the fission fragments of ^{235}U.

	Light fragment	Heavy fragment
M(amu)	95	139
Z	41	57
ϵ_0 (MeV)	99	68
$NR(\epsilon_0)$ (cm^{-2})	1.8×10^{20}	1.44×10^{20}

TABLE II. Computed results for the fission fragment slowing down parameters.

Ion	Light	Heavy
$\frac{h(Z_i,Z_g)}{N}$ (cm^3/s)	7.76×10^{-12}	6.73×10^{-12}
$N\tau$ (s/cm^3)	2.83×10^{11}	3.26×10^{11}
$\epsilon_0/N\tau$ (eV cm^3/s)	3.50×10^{-4}	2.09×10^{-4}
k_ϵ (eV cm^3/s)	3.80×10^{-4}	2.77×10^{-4}
$k_i(u_{ex})$ (cm^3/s)	5.19×10^{-6}	3.98×10^{-6}
k_{ex} (cm^3/s)	3.18×10^{-6}	2.51×10^{-6}

with $\epsilon_0/N\tau$ for both fission fragments. The calculated k_ϵ is evaluated for energy losses greater than the first excitation threshold for neon (16.6 eV). The two methods are independent and the comparison shows that the energy of the ions is well accounted for with this method.

We next consider the energy spectrum of the product electrons, which is the relative ionization rate of the gas by the fission fragments as a function of the product electron energy. Figure 2 shows the electron spectrum, which is sharply peaked at low energy. For comparison we also show the electron spectrum for ionization by a 1-MeV primary electron (as in an e beam plasma) assuming the form given by Opal, Peterson, and Beaty,[7] where

$$\Psi(\epsilon)\sim 1/[1+(\epsilon/\xi)]^2. \tag{13}$$

The electron spectrum from the e beam has a non-Maxwellian high-energy tail in addition to a generally higher T_e than in the fission fragment pumped case. This means that in fission fragment pumped plasmas, more of the product electron energy goes into lower-energy excitations than into high-energy excitations and ionization. This can also be seen in the average energy of the product electrons. For fission fragment pumping $\langle\epsilon\rangle_{FF}=40$ eV and for the 1-MeV e beam ($\xi=24$ eV for neon)

$$\langle\epsilon\rangle_{e\,\text{beam}}=2(\xi/\pi)\ln(\epsilon_{\text{beam}}/2\xi)=150\ \text{eV}.$$

Therefore, one can expect 3–4 more ionizations by the product electrons in an e beam compared to those generated by the slowing down of fission fragments.

Finally, we examine the energy deposition by the fission fragments. The ratio of the energy loss rate to the ionization rate gives the average energy per electron/ion pair created directly by the fission fragments. For our case we have

$$W_{FF}=k_\epsilon(u_{ex})/k_i=71.6\ \text{eV}. \tag{14}$$

The total W value will also include contributions from ionization by energetic product electrons, which will yield a value lower than that for ionization directly by the fission fragments. By comparing the rates for excitation and ionization,

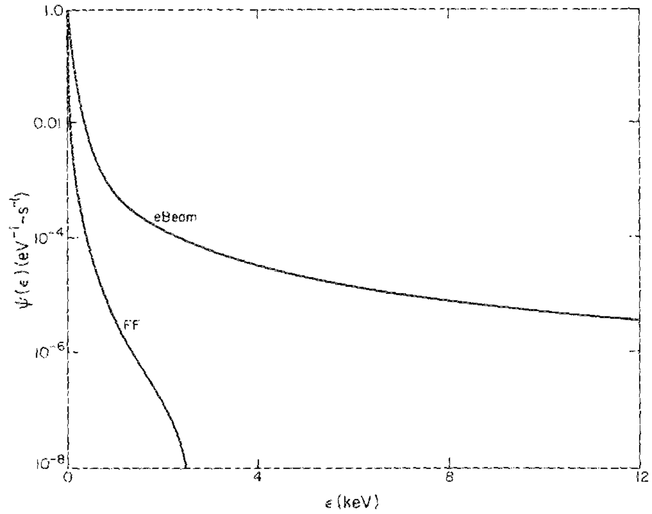

FIG. 2. The electron spectra (electrons/eV s) produced by the slowing of a 1-MeV e beam (upper curve) and for the fission fragments of ^{235}U in neon. Both curves are normalized to a peak value of 1.

we get $k_{ex}/k_{ion}=0.62$ excitations per ionization caused directly by the fission fragments.

To summarize, we have developed a method to describe the energy deposition by energetic heavy ions stopping in a rare gas and have derived the rates of direct ionization and excitation of the gas by fission fragments. Electronic excitation and ionization accounts for over 90% of the energy of the fission fragments; the remainder results in gas heating, important only at low ion velocities. We have also shown that the spectrum of electrons produced by fission fragment ionization is shifted to lower energy than that produced by an e beam, and a higher fraction of the pump energy goes into atomic excitations with fission fragment pumping. The W value for ionization directly by the fission fragments in neon is 70 eV/electron. Future extensions of this work will incorporate these results into a more complete scheme that will also consider the kinetics of the product electrons. This formulation will yield a total W value that can be compared to e beam results.

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