IODINE FLUORESCENCE SCHEMES FOR THRUSTER DIAGNOSIS

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OUTLINE

1. Iodine as a propellant as a Hall thruster propellant

2. Laser induced fluorescence

3. Ionized iodine emission spectroscopy measurements

4. I II LIF

5. Summary and future work
**Why is Xenon the Hall Thruster Propellant of Choice?**

**Xenon**
- High mass (131 amu)
- Relatively low ionization potential of 12.1 eV
- Inert (as opposed to Cs and Hg)
- Storage possible at specific density of 1.2
- Low concentration in air (90 ppb) so expensive and difficult to obtain in large quantities.

**Krypton**
- Lower mass (83.8 amu)
- Higher ionization potential of 14.0 eV
- Lower storage density
- Much lower cost

*Images from www.busek.com*
WHY NOT ARGON OR BISMUTH?

Argon
- Even lower mass (40 amu)
- Higher ionization potential of 13.6 eV
- Lower storage density
- Much lower cost

Bismuth
- High mass (209 amu)
- Lower ionization energy (7.29 eV)
- High storage density (solid at 9.78 g/cc)
- Very high boiling temperature of 1,564 ºC

*Images from www.busek.com
**WHY NOT IODINE?**

**Iodine**

- Nearly identical mass (126.9 amu)
- Diatomic in natural state (253.8 amu)
- Lower ionization potential of 10.45 eV (atom)
- Higher ionization potential of 13.6 eV
- Solid storage density of 4.9 g/cc
- Vapor pressure of 100 Pa at 39 °C
- Much lower cost and easy availability
- Difficult to pump in the laboratory
- Boiling point of 183° C

*Images from www.busek.com*
Laser induced fluorescence (LIF) primer

Species for single photon and 2-photon LIF:
- Ar I (dye and diode laser)
- Ar II (red and IR diode laser)
- Xe I (TALIF)
- Xe II (dye laser)
- He I (dye and diode laser)
- Kr I (TALIF)
- H I (TALIF)

Doppler shifted particle absorption distribution

\[ \nu = \nu_0 (1 - \nu \cdot \mathbf{k}_L / c) \]

\[ k_B T = \left( mc^2 / 8 \ln 2 \right) \left( \Delta \nu_{1/2} / \nu_0 \right)^2 \]
Typically we begin our three-level LIF schemes for low-temperature plasmas with excitation from a low-lying metastable state.

Ar II

diode laser

$4s^4P_{3/2} \rightarrow 4p^4D_{5/2} \rightarrow 3d^4F_{7/2}$

$442.72 \text{ nm}$

$668.61 \text{ nm}$

$T_{\text{Ar II}} = .22 \text{ eV}$

Ar II
dye laser

$4s^2D_{5/2} \rightarrow 4p^2F_{7/2} \rightarrow 3d^2G_{9/2}$

$461 \text{ nm}$

$611.6616 \text{ nm}$

Stark broadening and natural linewidth are ignorable. Zeeman splitting ignorable for perpendicular injection. For parallel measurements, single circular polarization used.
Occasionally non-metastable and 4-level schemes are employed for LIF on He I and Ar I.

**Ar I diode laser**
- 750.59 nm (4p' (2P^0_1/2)_0 → 4s' (2P^0_1/2)_1)
- 667.91 nm (4s' (2P^0_1/2)_0 → 4s (2P^0_3/2)_1)

**He I diode laser**
- 501.71 nm (2^1S → 3^1P)
- 667.99 nm (3^1P → 3^1D)

Excitation transfer:
- 667.99 nm

T_{Ar I} = 0.03 eV
T_{He I} = 0.03 eV

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CUTTING EDGE OF LIF TECHNIQUES

- Confocal optics
- 3D volumetric measurements of flows
- TALIF for Kr, Xe, H, and D
- Multiplexed parallel and perpendicular measurements
CONFOCAL LIF OPTICS UPGRADE EMPLOYS CORRECTIVE MENISCUS LENS

Completely fiber coupled apparatus capable of looking down the “throat” of a thruster
Excellent signal-to-noise and spatial resolution obtained with high power dye laser
FULLY PORTABLE DIODE LASER CONFOCAL LIF DEMONSTRATED IN ARGON

Excellent signal-to-noise and spatial resolution obtained with fiber coupled diode laser
**IODINE ION (I II) LASER INDUCED FLUORESCENCE**

Iodine ion (I II) single photon (LIF) scheme proposed by Hargus et al. [2012]
- Initial state is metastable
- Emission line is one of three decay paths
- Pump line accessible with diode lasers or Matisse dye laser with Pyridine dye and a 532 nm pump laser.

Iodine ion (I II) two photon (TALIF) scheme possible
- Initial state is the highly populated ground state.
- Could do resonant fluorescence and collect at full transition energy

Molecular iodine fluorescence
- Standard for LIF reference
- I$_2^+$ LIF scheme not yet identified
IODINEION(III) HYPERFINE SPLITTING

Iodine – 53 protons + 74 neutrons = 127 nucleons (odd)

- Hyperfine splitting from coupling of nuclear spin to angular momentum
- No existing experimental measurements of the splitting
- Hargus et al. [2012] described the selection rules, proposed the relative intensities, and parameterized the energy splittings in terms of the magnetic dipole moment and the electric quadrupole moment.

- Total angular momentum: \( F = I + J \)
  - Angular momentum \( J \) of atom is no longer sufficient
  - Nuclear spin \( I \) is coupled to \( J \)
  - Total angular momentum is now \( F = I + J \)
  - Individual values of \( F \) are given by

\[
F = J + I, J + I - 1, ..., |J - I|
\]

- Selection Rules
  - Transitions between \( F \) values of upper/lower states
    \[
    \Delta F = 0, \pm 1 \quad \Delta F \neq 0, \text{ if } F = 0
    \]
- Energy separation of spin split states
  - Constant \( A \) is a function of magnetic dipole moment
    \[
    \Delta E_M(F) = \frac{1}{2} A [F(F + 1) - J(J + 1) - I(I + 1)] = \frac{A}{2} C
    \]
  - For \( I \geq 1 \) electric quadrupole moments also present
    \[
    \Delta E_F = \Delta E_M + \Delta E_Q = \frac{AC}{2} + B \left[ C(C + 1) - \frac{4}{3} J(J + 1) I(I + 1) \right]
    \]
  - Constants \( A \) and \( B \) derived from experimental data...
IODOINE ION (I II) HYPERFINE SPLITTING

\[ 5d^5D_4^0 \rightarrow 6p^5P_3 \]

Relative intensities estimated from Russell-Saunders coupling

\[
F - 1 \rightarrow F: S = \kappa \frac{(J + F + I + 1)(J + F - I)(J - F + I + 1)(J - F - I)}{F}
\]

\[
F \rightarrow F: S = \kappa \frac{J(J + 1) + F(F + 1) + I(I + 1)}{F(F + 1)} (2F + 1)
\]

\[
F + 1 \rightarrow F: S = -\kappa \frac{(J + F + I - 2)(J + F - I + 1)(J - F + I)(J - F - I - 1)}{(F + 1)}
\]
EXPERIMENTAL APPARATUS

Same apparatus used by Hargus et al. [2012]

- Microwave discharge in resonant cavity
- Matisse dye laser for pumping
- Perpendicular fluorescence collection
- Cooling “finger” to reduce pressure in sealed quartz tube

$\lambda = 516.12 \text{ nm}$
**Emission Spectroscopy Confirms States Available**

- Emission intensity measured with 1.3 m spectrometer
- Pressure controlled with temperature of cold finger: \( \log_{10}P(\text{Torr}) = 18.8 - \frac{3594}{T_{cf}} + 0.00044T_{cf} - 2.98\log_{10}T_{cf} \)

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**516.12 nm Signal vs. Power**

- Count [A.U.]
- Power [W]

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**516.12 nm Signal vs. Temperature**

- Count [A.U.]
- \( T_{cf} \) [C]

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- Lineshape spans 6 GHz
- Clear hyperfine structure evident
- Center of gravity of lineshape shifted from predicted rest frame frequency
- Nonlinear fit using the four largest predicted hyperfine peaks yields incomplete fit and large ion temperatures (~ .15 eV)
Corrected lineshape still shifted from predicted rest frame frequency by \( \sim 0.75 \) GHz.

An \( \sim 500 \) m/s ion velocity error if left uncorrected.
I II LIF AMPLITUDE VERSUS SOURCE PRESSURE

- Emission intensity from integrated LIF signal
- Pressure controlled with temperature of cold finger
Hyperfine structure is the same with injection from either end of source.

Fits including hyperfine structure needed to determine ion temperature and rest frame line frequency from measured spectrum.
- Inclusion of the 11 lines predicted to have the largest amplitudes reproduces the measured line shape.

- The line amplitudes were not constrained to the predicted values but the line spacing was parameterized in terms of the magnetic dipole and electric quadrupole terms.

- Values of the magnetic dipole and electric quadrupole terms are of the same order of magnitude of those determined for similar sized atoms/ions.

- Common ion temperature of 0.085 eV determined from fit. Ion temperatures of of ~0.1 to 0.3 eV typical of other lamp discharges. Average ion temperature from hundreds of different fits ~ 0.2 eV.

\[ T = 0.0851 \text{ eV} \]
\[ r^2 = 0.9991 \]
\[ A_{\text{upper}} = 122.1 \text{ MHz} \]
\[ A_{\text{lower}} = 329.9 \text{ MHz} \]
\[ B_{\text{upper}} = -105.6 \text{ MHz} \]
\[ B_{\text{lower}} = -1237.5 \text{ MHz} \]
SUMMARY AND FUTURE WORK

- I II LIF scheme confirmed
- Pressure dependence of LIF intensity consistent with emission spectroscopy results
- Continue to investigate possibility of pressure and/or power broadening effects
- Use a second probe beam to measure the Lamp dip of each hyperfine line to improve understanding of hyperfine structure.
- Apply static potential along source tube to drive flows
- Test I II LIF scheme on commercial plasma thruster