Absolute photon cross sections for Balmer lines from proton-SO_2 collisions

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[1] Observations of atomic emissions from the Io plasma torus and previously published laboratory work suggest that proton collisions with SO_2 may be a source of some of the spectral lines. We present an analysis of Balmer series lines seen in the spectra of collisions of protons with SO_2 over the range of 50 to 250 keV. Absolute emission cross sections for these lines are measured to be on the order of 10^{-19} cm^2 and are in rough agreement with a parametric model for electron capture which supports charge-transfer ionization of the SO_2 target.

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1. Introduction

[2] Data from the 1996 Galileo spacecraft flyby of Io, the innermost of the Galilean moons, confirmed the presence of H+, O+ and S+ [*Williams et al.*, 1996] in the Io plasma torus. This plasma consists of ionized ejecta (mainly sulfur and oxygen) confined by Jupiter's magnetosphere into a torus shape that rotates around the planet. Tidal forces from Jupiter cause Io to be volcanically active producing plumes of S_2 and SO_2. Additional data from Galileo has provided extensive information concerning ultraviolet emissions from Io [*Hendrix et al.*, 1999]. This all suggests that measurements of proton-SO_2 cross sections for photon emission could prove useful in the analysis of the complex interactions on, and near, Io.

[3] Emission lines from neutral and ionized oxygen and sulfur have been observed [*Clarke et al.*, 1994; *Geissler et al.*, 1999] in the near VUV and the visible spectrum, emanating from the atmosphere of Io. The primary source of these emissions appears to be collision processes involving low-energy electrons and Io's atmospheric constituents [*Miller and Becker*, 1986; *Ajello et al.*, 1992; *Bhardwaj and Michael*, 1999; *Michael and Bhardwaj*, 2000]. However recent calculations of the proton energy spectra within $20R_{Io}$ [*Paranicas et al.*, 2003] show a significant intensity for protons of energies greater than 100 keV. Collisions between these protons and the various species of atoms and molecules present in the Io ejecta are a likely source of emission and may be competitive with electron collisions in particular regions of the Io environs. In a previous article [*Kiehling et al.*, 2001] we presented the emission spectrum produced by $H^+ - SO_2$ collisions in the wavelength region of 380–800 nm which showed numerous lines from neutral and ionized sulfur and oxygen. That work also showed strong Balmer lines from hydrogen. The range of proton energies was from 50 to 250 keV.

[4] The surprising report of HI Lyman-alpha emission near the poles of Io [*Roesler et al.*, 1999] raises the possibility that protons may be responsible for some of that moon's auroral emissions through electron capture collisions. *Bouchez et al.* [2000] failed to detect HI Balmer-alpha emissions but their flux threshold was too high to measure the Balmer line given the level of HI Lyman-alpha previously reported.

[5] In this paper we present photon emission cross sections for the Balmer lines seen in the *Kiehling et al.* [2001] study. These are relevant to the charge exchange (electron capture) process in the ionization of SO_2. We also compare these results with a parametric model for electron capture and direct ionization cross sections, developed by *Rudd et al.* [1983], for protons on molecular targets.

2. Experimental Approach

[6] Details of the experimental approach have been published earlier [*Kiehling et al.*, 2001]. The protons are produced by a Pellatron accelerator which has a maximum terminal voltage of 1 MV and can produce a usable beam from 50 keV to 1 Mev. The beam is mass and energy analyzed by a 15° magnet with an uncertainty in beam energy of less than 1%. The beam is collimated to a diameter of ~3 mm upon entering a differentially pumped target chamber.

[7] The target gas cell is aligned along the beam path with an adjustable viewing slit along this length. The gas pressure is regulated with a precision needle valve and pressure is measured with a capacitance manometer. The gas temperature is measured with a calibrated thermistor.

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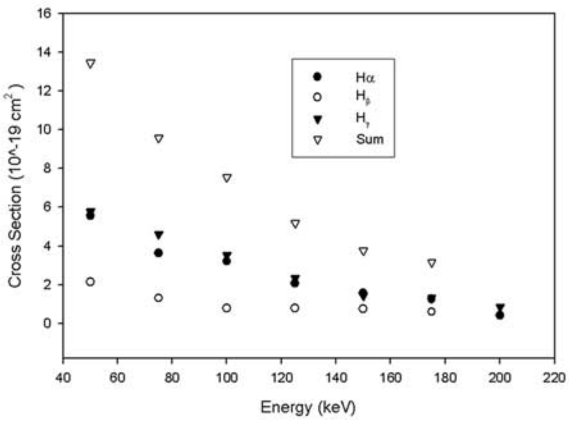

Figure 1. Absolute photon cross sections for H434.0 nm, H486.1 nm, and H656.3 nm and the sum of these lines.

[8] The photons emitted 90° to the beam path are directed through a lens system that includes a linear polarizer and are focused onto the entrance slit of a 0.25-m Oriel spectrometer. The light is detected with a 1024 × 256 cooled charge coupled device (CCD, Andor Technology, South Windsor, Connecticut). The spectral resolution of the system is 0.8 nm.

[9] Single-collision conditions are maintained by ensuring that the photon counts are linear with respect to both target pressure and 1 μA beam current. The CCD required correction for thermal noise, electronic noise, unequal pixel response, and wavelength-dependent sensitivity. The spectrometer was calibrated by using an argon-mercury lamp. The wavelength sensitivity of the system was established using a National Institute of Standards and Technology (NIST) traceable standard lamp. Anisotropy of the radiation is accomplished by standard procedure using parallel and perpendicular polarizations of the beam.

3. Cross-Section Calculation

[10] We calculate the photon emission cross section from the fundamental equation:

$$J_{ij} = \sigma NIL, \tag{1}$$

where J_{ij} is the number of photons per second from the transition i to j, σ is the cross section, N is the target density, I is the beam current (protons s^{-1}), and L is the interaction length. J_{ij} is calculated from the gross photon counts by applying the above listed corrections. See *Kiehling et al.* [2001].

[11] Because of the inevitable leakage of gas up the beam line and the consequent neutralization and outscattering of the beam, corrections to the emission cross section were made using standard techniques [*Holland et al.*, 1990; *Kiehling et al.*, 2001]. One major correction to the data is needed due to the fact that we are observing projectile emissions rather than target emissions. The correction is twofold in nature. The first part involves correcting for the motion of the radiating hydrogen atoms vis-à-vis the lifetimes of the radiating states. Also, since it is impossible to confine the target gas entirely within the gas cell, some protons will undergo the charge exchange collision before reaching the gas cell. Thus we will have some hydrogen atoms leaving the observation region before radiating and, also, some entering the observation region from "upstream". Both of these effects must be taken into account in the final determination of the emission cross section.

[12] We first calculate the effect of the lifetime of the radiating states. Initially, we will assume a static gas target of constant pressure (density). For a given state lifetime, τ, the number of atoms radiating at any time is given by

$$J = J_o e^{-t/\tau} \tag{2}$$

where J is the number of radiated photons/s, and J_o is the initial photon radiation rate. Now as we let the radiating atoms move with velocity v, we observe the radiation along their path between x, and x + l, where l is the length of our target gas cell slit. By simply calculating the total emission minus the emission before the slit plus the emission after the slit, we get the emission from the slit to be

$$J = J_o e^{-x/v\tau}\left[1 - e^{-l/v\tau}\right] \tag{3}$$

Now the emission rate is related to the cross section along a path dx by the standard relation:

$$dJ_o = \sigma I N_o dx \tag{4}$$

where I is incident projectile flux in particles/sec, and N_o is the target density in particles/cm^3. In our case the target density is no longer constant due to leakage up the beam line. Using the standard diffusion equation we can say the target density varies along the beam path by

$$N = N_o e^{-k(x)} \tag{5}$$

where k is an experimentally determined diffusion constant. In our case we measured k by noting the pressure in the gas cell and also the pressure as measured by a gauge that is about 2 m upstream from the cell. Combining equations (4) and (5), and then inserting into equation (3), we get for the total emission as seen from our slit

$$J_c = \sigma I N_o \int_0^\infty e^{-kx} e^{-x/v\tau}\left[1 - e^{-l/v\tau}\right] dx \tag{6}$$

Table 1. Emission Cross Sections for H656.3 nm, H486.1 nm, and H434.0 nm and the Sum of These Lines[a]

Energies, keV	Hα (656.3 nm)	Hβ (486.1 nm)	Hγ (434.0 nm)	Sum
50	5.6	2.1	5.8	13.4
75	3.6	1.3	4.6	9.6
100	3.2	0.8	3.5	7.5
125	2.1	0.8	2.3	5.2
150	1.6	0.8	1.4	3.8
175	1.3	0.6	1.3	3.2
200	0.4		0.8	

[a]Cross sections values are in 10^{-19} cm^2.

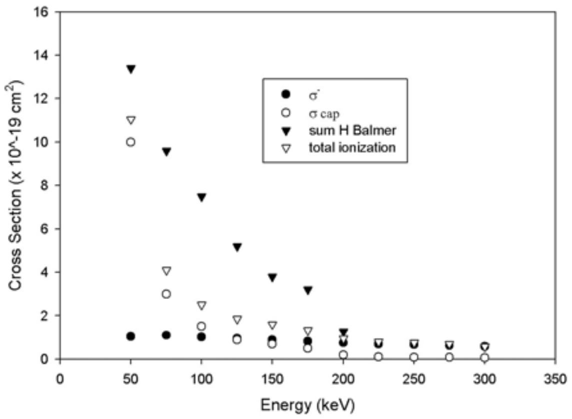

Figure 2. Calculated cross sections versus energy for direct ionization capture and total ionization. Measured cross section for the sum of the Balmer lines is included for comparison.

which easily integrates to

$$J_c = \sigma I N_o \left(k + \frac{1}{v\tau} \right) \left[1 - e^{-l/v\tau} \right] \qquad (7)$$

This correction ranges from increasing the Hα cross sections by about 60% at 50 keV impact energy, to decreasing the Hγ cross sections by about 8% at 200 keV.

4. Results

[13] The Balmer lines (Hα and Hβ) at 656.3 nm and 486.1 nm, are observed to be among the most prominent lines in the H^+-SO_2 emission spectrum (380–800 nm) for collisions at 200 keV [*Kiehling et al.*, 2001]. The Balmer line (Hγ) at 434.0 nm is less prominent but still very distinct. This indicates the importance of charge transfer to the incoming proton and the resulting ionization. Figure 1 shows the absolute emission cross sections for the three Balmer lines over the energy range of 50–200 keV and the sum of these lines. Uncertainties in these measurements are on the order of 12%. This is larger than cited by *Kiehling et al.* [2001] due to the lower signal to noise for these lines, as compared to the very strong 777 nm line of oxygen which was measured in that paper.

[14] By summing the net area of all the lines in the spectrum we calculated the percentage yield of the Balmer lines to be 15.5% (Hα, 4.4%; Hβ, 4.8%; Hγ, 6.3%). Table 1 gives these photoemission cross sections.

[15] To further explore the relative importance of the capture process we applied the parametric model for electron capture and direct ionization cross sections developed by *Rudd et al.* [1983] for protons on various molecular targets to our collisions. We calculated σ^- (ionization cross section) and σ_{cap} (capture cross section) for protons on SO_2. Because of the variance in the fitting parameters the uncertainty in this parametric model is 50%. Figure 2 shows the modeled cross sections. The summed H Balmer lines cross section is included for comparison. Note that the modeled capture cross sections compare favorably with our total emission cross section for the Balmer lines. However the cross sections appear to more closely follow the trend for capture rather than direct ionization. This supports the importance of capture for this process.

[16] If we calculate from the parametric model the percentage contribution of σ_{cap}, it varies from 87% of the total ionization cross section at 50 keV to 8.6% at 300 keV. At 200 keV it is 22%, which compares with our value of 16% of the total yield. Of course our values do not include Lyman or Paschen emissions. These are also likely to be occurring due to capture and thus the low yield is not surprising.

5. Conclusions

[17] We have shown that in the rich spectrum produced by proton impact on SO_2, charge transfer plays an important role. Since the energy range we have studied parallels the range of proton energies seen in the Io torus these observations present the opportunity to model the collision processes. Using the work of *Rudd et al.* [1983], it may be possible to estimate the amount of direct ionization by protons in the torus as compared to capture.

[18] Proton collisions might also account for the detection of H Lyman emission at the poles of Io. The prominence of H Balmer lines in the p-SO_2 collision spectrum suggests that charge transfer in the collision process $H^+ + SO_2 \rightarrow H^* + SO_2^+$ is responsible for the H Lyman observation.

[19] Finally we note that while most of the analysis of photon emission from Io and its vicinity presume the source to be electron collisions, our cross sections lie within an order of magnitude of those for comparable electrons (UV emission) from *Ajello et al.* [2002]. Therefore the contribution of proton collisions to the complex issue of Iogenic emissions remains a viable complement to those of electrons.

[20] We plan to continue this work by expanding the limits of the spectrum to 200 nm and 900 nm. Additionally we will obtain data for O+ and S+ beam collisions with SO_2.

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