The yield of air fluorescence induced by electrons

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***Abstract*—The fluorescence yield for dry air and pure nitrogen excited by electrons is calculated using a combination of well-established molecular properties and experimental data of the involved cross-sections. Particular attention has been paid to the role of secondary electrons from ionization processes. At high pressure and high energy, observed fluorescence turns out to be proportional to the ionization cross-section which follows the Born–Bethe law. Predictions on fluorescence yields in a very wide interval of electron energies (eV–GeV) and pressures (1 and 1013 h Pa) as expected from laboratory measurements are presented. Experimental results at energies over 1 MeV are in very good agreement with our calculations for pure nitrogen while discrepancies of about 20% are found for dry air, possibly associated to uncertainties in the available data on quenching cross-sections.**

I. Introduction

The charged particles, mostly electrons, from extensive air showers -EAS- generated by ultra-high energy cosmic rays -UHECR- interact with nitrogen molecules emitting fluorescence radiation. This radiation provides a precise determination of the longitudinal profile allowing the reconstruction of the primary properties. Fluorescence telescopes are being used by the Pierre Auger Observatory [1] to operate simultaneously with a giant air shower array.

The HiRes collaboration has reported measurements of the energy spectrum of UHECRs [2], using the fluorescence technique, which are in disagreement with those of the AGASA air shower array [3]. In order to achieve a reliable energy calibration of a fluorescence telescope, accurate values of the air fluorescence yield are required.

II. Theoretical considerations

In the wave-length interval of interest in the fluorescence technique, i.e., 300-406 nm, the light comes from the first negative system 1N of $N_2^+(B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+)$ and the second positive system 2P of $N_2(C^3\Pi_u \rightarrow B^3\Pi_g^+)$.

A. Fluorescence yield

The fluorescence yield $\varepsilon_{vv'}$ for a transition in a given band system is defined as the number of fluorescence photons emitted in the molecular transition v - v' per incident electron and unit path length, where v and v' represent the vibrational quantum numbers of the upper and lower electronic states of that band system, respectively.

At very low pressures the fluorescence yield $\varepsilon_{vv'}$ is equal to the product of the molecular density N of N_2 and the optical cross section $\sigma_{vv'}(E)$ for the electron energy, defined as the product of the excitation cross section $\sigma_v(E)$ for the upper level and the relative probability $B^{vv'}$ -branching ratio- of the v - v' transition.

$$\varepsilon_{vv'} = N\sigma_{vv'}(E) = N\sigma_v(E)B^{vv'}. \qquad (1)$$

B. Contribution of secondary electrons

At usual working pressures (P ~ Torr or more), the collisional quenching and the contribution of secondary electrons ejected in ionizations must be taken into account. It can be demonstrated [4,5] that

$$\varepsilon_{vv'} = N\underbrace{\frac{1}{1+P/P'_v}}_{\text{Quenching}}\left(\sigma_{vv'}(E) + \underbrace{\alpha_{vv'}(E,P)\sigma_{ion}(E)}_{\text{Secondary electrons}}\right), \qquad (2)$$

where P'_v is the characteristic pressure for the gas, $\sigma_{ion}(E)$ is the ionization cross section for the primary electron, and $\alpha_{vv'}(E,P)$ is the fraction of the secondary electrons that excite v - v' emission.

The parameter $\alpha_{vv'}(E,P)$ can be calculated by means of a Monte Carlo simulation. At atmospheric pressure and primary energy $E > 10^5$ eV, $\alpha_{vv'}$ is nearly energy and pressure independent.

C. Born-Bethe behavior

At high pressures, the contribution of secondary electrons is non-negligible for the 1N system while is dominant for the 2P system (see below). As a result, the fluorescence yield is proportional to the ionization cross section (not to the stopping power), which follows a relativistic Born-Bethe law.

$$\sigma = \frac{A}{\beta^2}\left\{\ln\left(C\beta^2\right) - \ln\left(1-\beta^2\right) - \beta^2 - \delta_F\right\}, \tag{3}$$

where β is the relativistic speed, A and B are constants, and δ_F is the usual density correction parameter included in the Bethe-Bloch formula for stopping power.

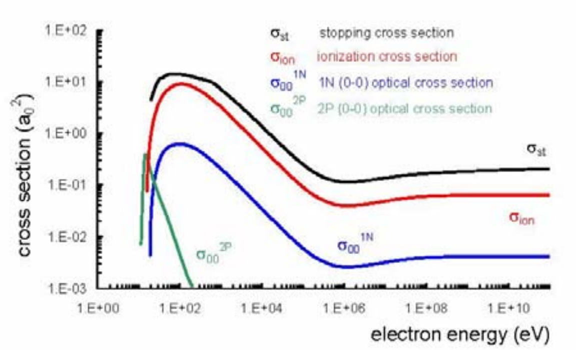

Fig. 1. Cross sections involved in fluorescence emission for air. Stopping cross section (proportional to the electron stopping power) follows a Bethe-Bloch behavior not exactly proportional to Born-Bethe law.

III. RESULTS

A. The first negative system

Many measurements at low energies of the optical cross-section σ_{00} corresponding to the strongest band at 391.2 nm of the 1N system are available in the literature. As can be seen in Fig. 1, σ_{00}^{1N} is proportional to the ionization cross section, so that the Eq. 3 provides us with a reliable value of σ_{00} (direct excitation) in the whole energy range.

At high pressure, quenching and secondary electrons contributions to ε_{00} have to been considered by means of Eq. 2, using the α_{00} values obtained by simulation. Very important contribution of secondary electron at high energy is found. As an example, Fig. 2 and 3 show ε_{00} as a function of electron energy for pure nitrogen and dry air respectively, at several pressures and a temperature of $T = 300$ K. Our predictions are in good agreement with direct measurements of Hirsh et al. [6], for dry air, while a clear disagreement with measurements of Nagano et al. [7], for both nitrogen and dry air, for which a two lines analysis had to be applied in order to subtract another band not separated by the spectroscopy filter.

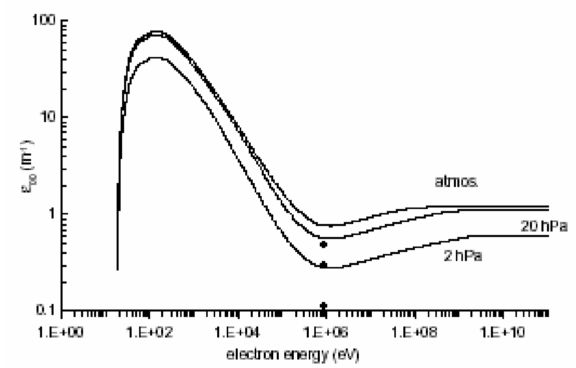

Fig. 2. Fluorescence yield for 1N (0-0) band for pure nitrogen at several pressures. Predictions of this work (continuous lines) are compared with experimental data of Nagano et al. [7] (●) at same pressures.

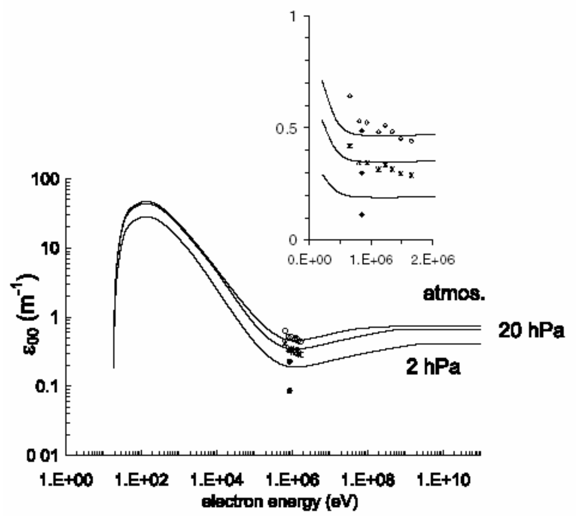

Fig. 3. Same as Fig. 2 for dry air. In addition, experimental values of Hirsh et al. [6] at 20 hPa (*) and atmospheric pressure (○) are shown for comparison.

B. The second positive system

The optical cross section σ_{00} for the 2P (0-0) band (see Fig. 1) shows a fast E^{-2} energy dependence due to the optically-forbidden nature of the 2P transitions. However at high energies and high pressures the 2P fluorescence even dominates over the 1N system. This feature can be explained taking into account the contribution of low energy secondary electrons, because of their higher probabilities for nitrogen excitation.

Figures 4 and 5 show the fluorescence yield ε_{00} calculated for the 2P (0-0) band as a function of electron energy at several pressures in pure nitrogen and dry air respectively. Experimental data at high energy are included for comparison, showing a good agreement.

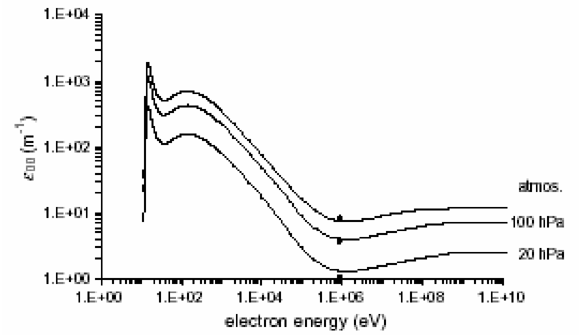

Fig. 4. Fluorescence yield for 2P (0-0) band for pure nitrogen at several pressures. Predictions of this work (continuous lines) are compared with experimental data of Nagano et al. [7] (●) at same pressures.

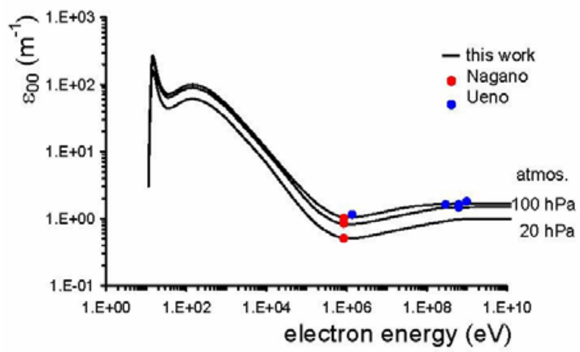

Fig. 5. Same as Fig. 2 for dry air. In addition, experimental values of Ueno [8] at atmospheric pressure are shown for comparison.

C. *Total fluorescence yield*

The parameter actually required for the calorimetric determination of the primary energy of EAS is the total fluorescence yield, i.e., the sum of the contributions of all molecular bands in the spectroscopic interval from 300 to 406 nm.

At high pressures ($P >> P'_v$), the relative intensities $\varepsilon_{vv'}$ for a given system can be approximated by

$$\varepsilon_{vv'} \approx q_{X\to v} B^{vv'} P'_v \,, \tag{4}$$

where the Franck-Condon factors $q_{X\to v}$, are calculated [9] for the excitation from the fundamental state X of the N_2 molecule to the upper level v. Therefore, the total fluorescence yield can be expressed in terms of two reference bands, e.g., 1N (0-0) and 2P (0-0), and the sum over the relative intensities of Eq. 4.

Figures 6 and 7 show the total fluorescence yield at high energies and at atmospheric pressure for pure nitrogen and dry air respectively, together with available experimental data. For pure nitrogen data are in agreement with our predictions while a fluorescence efficiency about 20% larger than [10] and [11] is

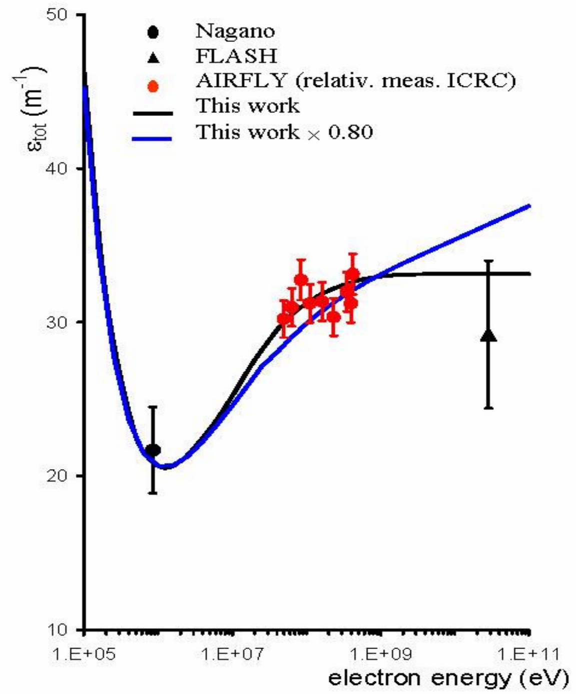

Fig. 6. Total fluorescence yield at high energy for pure nitrogen. Prediction of this work are compared with absolute measurements of Nagano et al. [7], and the FLASH collaboration [11]. Relative measurements of AIRFLY [12] and the Bethe-Bloch function normalized at 100 MeV and 1 MeV respectively are also shown.

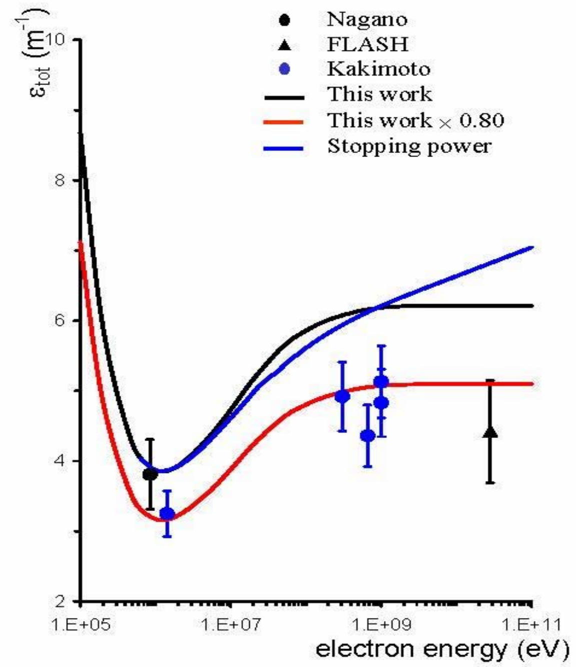

Fig. 7. Same as Fig. 6 for dry air. Absolute measurements are of Nagano et al. [7], Kakimoto et al. [10] and the FLASH collaboration [11]. Results of this work reduced by 20% are also shown.

predicted for air. This lead us to suspect that the ratio $P'_{air}/P'_{nitorgen}$ assumed in our calculations has been overestimated by about a 20%.

On the other hand, the stopping power law for electrons (Bethe-Bloch) shows a noticeable deviation with respect the fluorescence yield, since at large E values a significant fraction of the electron energy loss is not deposited inside the fluorescence cell. See [5] for more details.

IV. CONCLUSIONS

Theoretical predictions of the air fluorescence induced by electrons as expected from typical laboratory experiments have been presented in a very wide range of energies and pressures. Particular attention has been paid to secondary electrons ejected in ionization processes.

Present model relies on several data on molecular physics, like branching ratios, quenching coefficients or secondary electron distributions, so the accuracy of its predictions is ultimately limited by the reliability of those data, which we are currently trying to improve.

The contribution of direct excitation of 1N system is calculated using low energy measurements of optical cross section with extrapolation to high energies as given by Born-Bethe law. The 2P direct excitation is negligible.

The contribution of secondary electrons is non-negligible for the 1N fluorescence and dominant for the 2P system.

At high energies and high pressures, the total fluorescence yield results proportional to the ionization cross section which also follows a Born-Bethe energy law.

Comparison of our predictions with available measurements shows a good agreement for pure nitrogen while some discrepancies are found for dry air, likely due to uncertainties in the quenching cross sections.

V. REFERENCES

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