Luminescence model with quantum impact parameter for low energy ions

H.S. Cruz-Galindo [a,*], K. Michaelian [b], A. Martínez-Dávalos [b], E. Belmont-Moreno [b], S. Galindo [a]

[a] *Instituto Nacional de Investigaciones Nucleares, Carretera México-Toluca, Km. 36.5 Salazar, Edo. de Méx., Mexico*
[b] *Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, 01000 México, D.F., Mexico*

Abstract

We have modified an analytical model of induced light production by energetic ions interacting in scintillating materials. The original model is based on the distribution of energy deposited by secondary electrons produced along the ion's track. The range of scattered electrons, and thus the energy distribution, depends on a classical impact parameter between the electron and the ion's track. The only adjustable parameter of the model is the quenching density ρ_q. The modification here presented, consists in proposing a quantum impact parameter that leads to a better fit of the model to the experimental data at low incident ion energies. The light output response of CsI(Tl) detectors to low energy ions (<3 MeV/A) is fitted with the modified model and comparison is made to the original model.
© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Scintillation; Detectors; CsI

1. Introduction

An analytical model of induced light production by energetic ions in scintillating materials, proposed by Michaelian and Menchaca (M–M) [1], closely fits the data from luminescent detector materials within a large range of energies of the incident ions (10–100 MeV/A). However, at lower energies, i.e. below 10 MeV/A [2], the experimental deviations from the predictions of the M–M model, indicate that there might be certain physical effects, important at low energy, that are not dealt with in the original model.

The M–M model is based on the distribution of energy deposited by secondary electrons produced through ionization along the ion track. In this model, the electrons initial energy ω_0 is found using an impulse approximation for the momentum transfer of the incident ion to electron. It is therefore assumed, that the collisions between the incident ion and the electrons of the medium last for a such a short time with respect to the classical atomic orbital period, that an impulse is given to

* Corresponding author. Address: Instituto Nacional de Investigaciones Nucleares, Dept. de Proteccion Radiologica, Apartado Postal 18-1027 Col. Escandon, C.P. 11801 Mexico D.F., Mexico. Fax: +52-5-329-7304.
E-mail address: scg@nuclear.inin.mx (H.S. Cruz-Galindo).

the electron without changing its position during the collision time. The electron is therefore constrained to move perpendicular to the trajectory of the ion. In this model, the electrons initial energy was shown to be [1]

$$\omega_0 = \frac{2}{m_e} \left[\frac{z^* e^2}{b_{min} v^2} \right]^2, \qquad (1)$$

where z^* is the effective charge of the ion [3] and v its velocity, m_e is the electron mass and e its charge. The impact parameter, b_{min}, is the minimum distance of approach between the electron and the ion track. A classical approximation for this impact parameter gives [1]

$$b_{min} = \frac{z^* e^2}{m_e v^2}. \qquad (2)$$

During its motion away from the ion's track, the electron deposits its energy radially according to its specific energy loss, dE/dr. Integration of an expression for the electron specific energy loss given by Linhard et al. [4] gives a power law relation between the practical range R and the initial electron energy ω_0 of form

$$R = a \omega_0^n. \qquad (3)$$

This relation has been verified by experiment [5], a is a constant which depends on the effective atomic mass and charge of the compound material and n takes the value of 5/3 [6].

By using a number of justifiable approximations, and including contributions from the backscattered electrons, the M–M model arrives at a general expression for the electron energy deposition density per unit path length, $\rho(r)$, of the incident ion as a function of the its effective charge z^*, its velocity v, the effective charge of the medium Z_{eff}, and the radial distance r from the trajectory of the ion [1],

$$\rho(r) = \frac{e^4}{n m_e} \frac{z^{*2}}{v^2} \frac{1}{r^2} \aleph \left[1 - \frac{r}{R_{max}} \right]^{d+1/n}, \qquad (4)$$

where $d = 0.045 Z_{eff}$, the number of electrons per unit volume of the material is $\aleph$ and the maximum range of electron is $R_{max} \sim a(2m_e)^n v^{2n}$ [1]. Here a is the constant and n is the power exponent defined in the electron range-energy relation (Eq. (3)).

To obtain a light output estimation from the energy deposition profile $\rho(r)$, the M–M model considers two basic assumptions; first, that the regional density of electron–hole pairs (e–h) or excited molecular structures (defined in the M–M theory as energy carriers) created in the scintillator material is, in the absence of quenching effects, proportional to $\rho(r)$, i.e. the energy deposition density; second, that the specific luminescence (per unit path length) of the ion dL/dx is proportional to the energy carrier density dN_e/dx, where N_e is the number of energy carriers.

Quenching effects, characteristic to each material, are introduced in the model by assuming that there is a maximum energy deposition density, greater than which there is recombination of the e–h pairs and the energy carrier density remains at a maximum constant value. This, in effect, is attained by assuming a limiting maximum energy carrier density ρ_q which is an inherent constant of the scintillator material and the only free parameter of the model. Therefore, corresponding to that particular value of ρ_q there is a distance r_q, from the incident ion track, at which $\rho(r) = \rho_q$ for $r < r_q$. The value of ρ_q is determined by obtaining the best fit of the model generated L versus E_0 curve (where E_0 is the incident ion energy) with the equivalent experimental curve, while varying ρ_q.

The second assumption, namely that the specific luminescence of the ion is proportional to the energy carrier density, implies that

$$\frac{dL}{dx} = C \frac{dN_e}{dx} = k \left[\pi r_q^2 \rho_q + \int_{r_q}^{R_{max}} 2\pi \rho(r) r \, dr \right], \qquad (5)$$

where C and k are overall normalization constants.

The integral is separated into two parts, the quenched ($0 \leqslant r < r_q$) and the unquenched ($r_q \leqslant r \leqslant R_{max}$) where r_q is obtained from Eq. (4) with $\rho(r) = \rho_q$.

In the present work, we have modified the M–M model by incorporating a quantum mechanical expression for the impact parameter (Eq. (2)) to obtain a better fit to the experimental data in the low energy region. In the following section we will briefly mention some of the factors that may affect the electron energy deposition density per unit path length $\rho(r)$ at low energies. Some of these

factors appear to be adequately dealt with the M–M approach while others do not. Comparison of the new approach to published experimental data is given in Section 3.

2. Modification of the M–M model

In principle, the M–M model justifiably neglects phenomena that are not important for ions traveling at intermediate energies such as: the polarization of the target material, and the nuclear interactions (nuclear stopping) between the incident ion and the material nuclei (excitations and reactions). The first is observed when, in the luminescent material, several atoms of the solid interact simultaneously with the ion. The collective effect of these on the energy deposition is considered macroscopically as the result of the dielectric polarization of the medium by their electric charge. However, for non-relativistic ions, polarization effects have only a small influence on the deposition of energy [7].

The total stopping cross-section of ions in matter can be divided into two parts: the interaction of the ion with target atom electrons (electronic stopping) and with the target nuclei (nuclear stopping). The nuclear stopping component is very small at ion energies above 0.2 MeV/A, for example, 1% of electronic stopping [8]. Since by far the main component of the light produced by the ions of interest in this work results from ion energies above 0.2 MeV/A, nuclear stopping will be ignored.

Additionally, as the incident ion traverses the medium and slows down to the order of the Bohr velocity, it begins to pickup electrons from the medium and hence reduces its effective charge. The value of this effective charge is adequately taken into account in the expression (4) by Montenegro's effective z^*. For very low velocities (when the ion has charge ≈ 1) the real charge presents marked discontinuities and the effective charge expression is no longer adequate. Fortunately, this effect is only important for energies below 0.2 MeV/A, therefore this effect is also be neglected in the present work. The expression for z^* is valid for ion energies above 0.2 MeV/A [3].

We suggest that the deviations of the M–M predictions from the experimental values at lower energies, lie, for the most part, in the classical approach of the M–M model to the impact parameter. The model considers that in an elastic classical collision there exists a minimum classical impact parameter given by Eq. (2) and this is determined considering the incoming ion as a classical particle. However, in a rigorous description, a particle has to be considered as a wave packet propagating in space with a group velocity equal to the particle velocity. The width, Δx, of this wave packet and the spread of the linear momentum, Δp, of its wave train components, are related through the Heisenberg uncertainty principle. Quantum mechanics thus gives a new limit for the minimum impact parameter $b_{\min}$ since an electron can only be localized with respect to the ion, with an accuracy that coincides with its De Broglie wavelength, that is $b_{\min_q} = \hbar/p$.

In the present work $b_{\min}$ is modified using the energy deposition expression determined by Bethe [7] and the de Broglie wavelength to obtain a new quantum impact parameter $b_{\min_q}$. This slight modification of the M–M model produces, as will be shown, a better fit to the low energy experimental data.

The minimum impact parameter, $b_{\min_q}$, using the De Broglie wavelength of the electron is

$$b_{\min_q} = \frac{\hbar}{p} = \frac{\hbar}{mv\gamma}, \qquad (6)$$

here $\gamma = \sqrt{1 - \beta^2}$, with $\beta = v/c$. Since $\beta \sim 0$ and $\gamma \sim 1$ for low energies, $b_{\min_q} = \hbar/mv$ is the quantum impact parameter that will substitute, in the M–M model, the classical impact parameter.

3. Results

Fig. 1 shows the experimental data of Martínez-Dávalos et al. [2], for the light output response (in arbitrary units) of a CsI(Tl) detector as a function of the incident energy for ^{1}H, ^{4}He and ^{12}C ion beams in the energy range of 1–3 MeV/A. The dotted lines correspond to the results of the original M–M model described in [1], using an optimal quenching energy density of 2.3×10^8 erg/g and
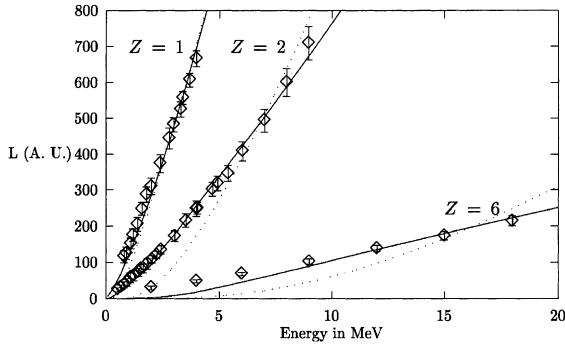
Fig. 1. Light-output response of the CsI(Tl) detector for ^{1}H, ^{4}He and ^{12}C ion beams [2]. The solid lines represent the predictions with the quantum impact parameter. The dotted lines represent the predictions with the classical impact parameter.

Table 1
Results for the χ^2 per degree of freedom comparison of original and modified models with the experimental data for the ion beams used in the 1–3 MeV/A range

Z	χ^2 (b_{min} classical)	χ^2 (b_{min_q} quantum)
1	4.67	2.52
2	33.97	0.76
6	19.97	4.71

the expression for the impact parameter as given by Eq. (2). The solid lines represent the predictions of the present work using an optimal quenching density of 8×10^8 erg/g and the quantum impact parameter of Eq. (6).

Table 1 compares the χ^2 per degree of freedom values of the model fit to the data with both the classical and quantum impact parameters. In the quantum case, the value of χ^2 is significantly reduced for all ions.

In conclusion, we have considered the effect of various phenomena which may have important consequences to the light production, within the frame work of the M–M model, at low incident ion energy. The most important appears to be use of a quantum minimum impact parameter b_{min_q}, since an electron can be localized with respect to the ion with an accuracy that coincides with its De Broglie wavelength. We have modified the M–M model in this respect and have shown that this simple correction improves significantly the χ^2 comparison of the model with the experimental data at low energies.

Acknowledgements

References

[1] K. Michaelian, A. Menchaca-Rocha, Phys. Rev. B 49 (1994) 15550.
[2] A. Martínez-Dávalos, E. Belmont-Moreno, K. Michaelian, A. Menchaca-Rocha, J. Lumin. 72–74 (1997) 769.
[3] E.C. Montenegro, S.A. Cruz, C. Vargas-Aburto, Phys. Lett. A 92 (1982) 195.
[4] J. Linhard, M. Scharff, H.E. Schiott, Math. Fys. Meddr. 33 (1963) 1.
[5] L. Katz, A.S. Penfold, Rev. Mod. Phys. 24 (1952) 28.
[6] K. Kanaya, S.O. Kayama, J. Phys. D 5 (1972) 43.
[7] E. Segré, Nuclei and Particles, W.A. Benjamin, New York, 1960.
[8] J.F. Ziegler, Handbook of Stopping Cross Sections for Energetic Ions in all Elements, Pergamon, New York, 1980.