Nuclear Instruments and Methods in Physics Research B2 (1984) 95-96
North-Holland, Amsterdam

RADIATION FROM THE CHARGE EXCHANGE OF HEAVY IONS IN MATTER

V.P. ZAIKOV, E.A. KRALKINA, Ya.A. TEPLOVA and V.P. PETUKHOV

Institute of Nuclear Physics, Moscow State University, Moscow 117234, USSR

I.B. MOROZOV

Physical Faculty, Moscow State University, Moscow 117234, USSR

A classical model for the calculation of the radiation due to heavy ion charge exchange in matter is proposed. The calculations were made for protons with energies of 10 to 500 keV in solid and gas targets, with atomic number, $Z_m = 7$.

The calculations have shown that the maximum of the spectrum corresponds to the frequency $\nu = v_p/(1/n_0\sigma_c + 1/n_0\sigma_e)$ where v_p is the proton velocity, n_0 is the target density, σ_c and σ_l are the electron capture and loss cross sections respectively.

In the passage of ion beams through solid and gaseous media, the density of the charged-particle current is changed repeatedly by electron capture and loss which must result in electromagnetic radiation; see fig. 1. The charged particle, for example, a proton, moving at a velocity v_p in the condensed matter, captures an electron from the atom at a point X_1 and gets neutralized. As a consequence, the electric current vanishes. At a point X_2, the proton loses an electron, which comes to rest. And so the electric current of the proton appears again. The electron capture and loss by a proton in a medium is a multiple process. For example, as the proton at the initial energy, E_p, of 100 keV comes to rest in nitrogen $Z_m = 7$, the particle charge is changed nearly 1500 times.

The intensity and spectrum of the radiation can be calculated by formulae [1], where the electric field is

$$E(t) \simeq \cdot \frac{n}{c^2 R} \frac{\sin\theta}{\left(1 - \frac{v_p}{c}\cos\theta\right)} \frac{\partial j}{\partial t'},$$

where $t' = t - R/c$, $t = x/v_p$, X coordinate of a moving ion, R is the distance from the point of observation, θ the angle between the direction of observation and ion motion, j the density of the current resulting from the charged particle motion, v_p the ion velocity, and $\boldsymbol{n}$ the unit vector of $\boldsymbol{E}(t)$.

In our case, $j(t)$ appears as a sequence of rectangular pulses; see fig. 1. Then the Fourier component of the electric field $E(t)$ is

$$E_m(\omega) = (\boldsymbol{E}(\omega)\boldsymbol{n}) = \frac{1}{\sqrt{2\pi}\, c^2 R} \sin\theta\, e^{i\omega R/c} \frac{e v_p}{\left(1 - \frac{v_p}{c}\cos\theta\right)^2} \times \sum_{m=1} (-1)^m e^{i\omega(t_m - [X(t_m)/c]\cos\theta)}$$

Here, t_m is the time of "switching on" and "off" of the current. The number of photons at a frequency ω per unit time per unit frequency and per unit solid angle is:

$$N(\omega) = \frac{R}{\hbar\omega} \frac{c}{2\pi} E(\omega) E^*(\omega).$$

The equation holds if the free path of the proton is in

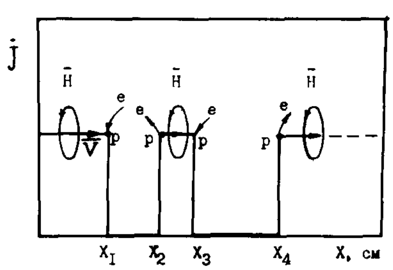

Fig. 1. Electron loss and capture by a proton in the passage through a medium.

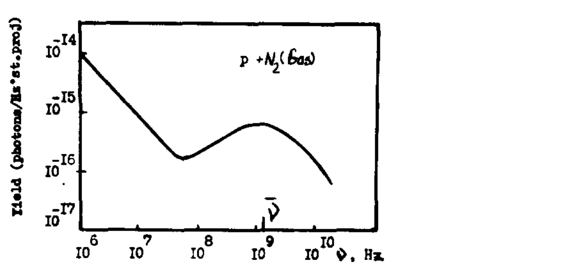

Fig. 2. The calculated spectrum of the radiation arising in the passage of protons through a gaseous medium, T-target length.

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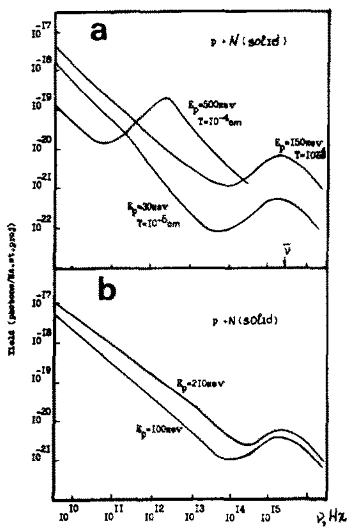

Fig. 3. The calculated radiation spectrum: (a) for the case without proton energy loss in the film and (b) when the proton comes to rest in the film [3], $n_o = 10^{23}$ atoms/cm^3.

excess of the size of the region of interactions between the protons and the target atom.

The spectra arising in the passage of protons with an energy of 20 to 500 keV through gases and solid dielectrics with $Z_m = 7$ have been computed. It was taken into account that the random character of electron capture and loss affects strongly the radiation spectrum. For example, the statistical uncertainty in the range data for protons with l_l, and without, l_c, an electron is in accordance to the distribution

$$f(l) = \frac{1}{l_{ol}} e^{-l/l_{ol}}, \qquad f(l) = \frac{1}{l_{oc}} e^{-l/l_{oc}},$$

where

$$l_{ol} = \frac{1}{n_o \sigma_l} \quad \text{and} \quad l_{oc} = \frac{1}{n_o \sigma_c}$$

are the corresponding mean values of l_l and l_c and n_o is the target density and σ_c and σ_l are the electron capture and loss cross sections, respectively.

In the calculations, the "switching on" and "off" of the current was assumed to be instantaneous.

The calculated spectrum of the radiation arising in the passage of protons through the gaseous medium with a density of 5×10^{16} atoms/cm^3, fig. 2 is within the SHF frequency band. The radiation has a broad

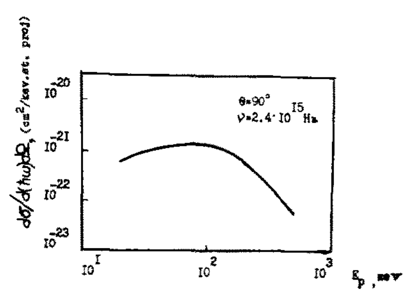

Fig. 4. Absolute cross section for the radiation in a solid film versus proton energy, $\theta = 90°$, $\nu = 2.4 \times 10^{15}$ Hz.

maximum at a frequency of $\nu = 2\pi/\omega \approx 10^9$ Hz which corresponds to the average rate of change in the current arising from the proton motion $\bar{\nu} = v_p/(1/n_o\sigma_c + 1/n_o\sigma_l)$. The values of σ_c and σ_l are taken from ref. [2]. Thus, the radiation spectrum provides direct information about the ion charge exchange in a medium.

The radiation spectrum for protons with an energy of 30 to 500 keV passing through thin dielectric films with a density $n_o \approx 10^{23}$ atoms/cm^3, fig. 3, shifts to the visible part of the spectrum, the local maximum of the radiation being observed; likewise in the passage of protons through the gaseous medium, at an average rate of change in the current j. A large number of photons at $\nu = 0$, figs. 2 and 3, contribute weakly to the total energy of the radiation and make up $\sim 10^{-7}$ of its magnitude.

The absolute cross section for the radiation in a solid film versus proton energy E_p at the maximum radiation intensity $\nu = 2.4 \times 10^{15}$ Hz, is given in fig. 4.

From the analysis of the calculations it follows that the passage of a charged particle through solid and gaseous media is accompanied by electromagnetic radiation whose spectrum provides information about the charge exchange process inside the target and is useful in estimating the cross sections for the corresponding charge exchange processes.

References

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[3] J.F. Ziegler, vol. 3, Hydrogen-stopping powers and ranges in all elements (Pergamon Press Inc., Oxford, 1977).