A review of X-ray imaging phosphors

S V MOHARIL
Department of Physics, Nagpur University, Nagpur 440010, India

MS received 15 March 1993; revised 13 September 1993

Abstract. The important methods of X-ray imaging use various phosphors. The phosphors
give light proportional to the amount of radiation. The light is emitted either as X-ray excited
fluorescence, phosphorescence, or due to stimulated, radiative recombinations of defects
generated by X-ray exposures. The role of phosphors in improving image quality and reducing
exposures to patients is important. Properties of various phosphors which can be used for
X-ray imaging applications are reviewed here.

Keywords. X-ray imaging; phosphors.

1. Introduction

Almost immediately after the discovery of X-rays by Röntgen, it was realized that
this radiation is not very efficient in affecting photographic emulsions. A search for phosphors, which are able to convert X-rays into visible radiation, was started. Pupin
(as quoted by Brixner 1987) found that CaWO$_4$ emits light upon X-ray incidence,
which affects photographic film more effectively than the X-rays themselves. Several
materials have since then been developed (Smets 1991). These will be reviewed under
the section on screen phosphors. Later, more effective ways of X-ray detection and
imaging using scintillators and photostimulatable phosphors were invented; these
will be discussed in the subsequent sections.

2. Screen phosphors

2.1 Mechanism

High energy ionizing radiation in the form of X-rays is absorbed by the lattice and
secondary charge carriers such as electron and hole pairs are created. After thermaliza-
tion, these pairs recombine, and this process ultimately results in the emission of
photons. Energy efficiency $\eta$ of the overall process is given (Robins 1980)

$$\eta = (1 - r_b) \frac{hv_a}{E} \eta_i Q,$$

where $r_b$ is the fraction of primary radiation scattered back, $hv_a$ the quantum emitted,
$E$ the average energy to generate one e–h pair, $\eta_i$ the efficiency for transfer of e–h
recombination energy to the activator, and $Q$ the quantum efficiency of luminescence
centre. Practically, screen phosphors are characterized by their speeds given by

$$S = AQD,$$

where $A$ is the absorption coefficient of phosphor and $D$ the detection efficiency
defined as

\[ D = \int \phi d\lambda / \int \phi d\lambda, \]

where \( D \) and \( \phi \) are sensitivity and flux respectively.

Screen phosphors should thus have high absorption of X-rays, high densities and stopping power, high luminescence efficiency, emission matching with the most sensitive range of the photographic materials (300–480 nm), not very long decay time (> 1 s), good radiation resistance, non-toxicity, good mechanical and chemical stability, etc.

Needless to say, a single material possessing all these characteristics has not been found, but compromising on some factor or the other, a phosphor can be found to suit the application.

2.2 Materials

2.2a \( \text{CaWO}_4 \): This is the earliest known phosphor, discovered by Edison (see Harvey 1957). Both excitation and emission take place in \( \text{WO}_4^- \) group. Emission is at 430 nm giving a \( D \) of 81\%. Of the constituent atoms only \( \text{W} \) (\( Z = 74 \)) gives dominant contribution to X-ray absorption. The energy efficiency is rather poor, being only about 5\%. Radiation resistance is also rather poor, but can be improved by adding \( \text{NaHSO}_4 \) which introduces shallow traps which are emptied at RT itself.

Efforts were made to replace \( \text{CaWO}_4 \) (Dutch patent 6917280, 1970; US patent 3,527,710, September 1970; Bates 1968; Ludwig 1972; Ludwig and Prener 1972; Stevels 1976). The materials have been systematically reviewed by Stevels and Pingault (1975). However, these materials were not found to be better than \( \text{CaWO}_4 \), due to one drawback or the other, e.g. \( \text{ZnS}:\text{Ag} \) is more sensitive than \( \text{CaWO}_4 \) at lower energies but image is sharper with \( \text{CaWO}_4 \). Better materials were found only after the seventies.

2.2b \( \text{LaOBr}:\text{Re} \): \( \text{LaOBr} \) doped with rare earths (Tb, Tm or Dy) were studied by Blasse and Bril (1967). An X-ray screen using \( \text{LaOBr}:\text{Ce}, \text{Tb} \) was reported by Rabatin (1971). The method of preparation of the phosphor and more detailed properties were given by Holsa et al (1980, 1981).

2.2c \( \text{M'}\text{ReTaO}_4 \): Rare earth tantalates crystallize in two types of structures designated as M type and M' type (Wolten 1967). Blasse and Bril (1970) studied \( \text{M'}\text{ReTaO}_4 \) for \( \text{Re} = \text{Gd}, \text{Y} \) and \( \text{Lu} \). Application to X-ray screens is described by Brixner and Chen (1983). These compounds have high density (7.56 g/cm\(^3\)) and little afterglow. The excitation and emission is in \( \text{TaO}_4 \) luminescence centre which is excited via charge transfer process. Emission is at 337 nm which is suitable for blue sensitive X-ray films. When small quantities (\( \approx 2\% \)) of Nb are incorporated, all the energy is transferred to niobate group emitting at 410 nm. Energy efficiency is 9\% and the detection efficiency 95\%.

2.2d \( \text{Gd}_2\text{O}_2\text{S}:\text{Tb} \): Rare earth oxysulphides doped with Tb were studied by Klassem and de Groot (1947) and Wickersheim et al (1969, 1970). They found 13\% efficiency for \( \text{La} \) oxysulphide and 18\% for the Gd compound. These materials also have high