Luminescence properties and energy transfer in Tb\(^{3+}\) and Eu\(^{3+}\) co-doped Ba\(_2\)P\(_2\)O\(_7\) phosphors

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The Ba\(_2\)P\(_2\)O\(_7\) :Tb\(^{3+}\), Eu\(^{3+}\) phosphors were synthesized by a high temperature solid-state reaction method in air atmosphere and their crystal structures, lifetime, luminescence properties, and energy transfer mechanism were investigated in detail. A series of characteristic emissions of Ba\(_2\)P\(_2\)O\(_7\) :Tb\(^{3+}\), Eu\(^{3+}\) phosphors were observed in the emission spectra at around 545 nm, 593 nm, and 613 nm when excited at 378 nm. The energy-transfer mechanism from Tb\(^{3+}\) to Eu\(^{3+}\) in Ba\(_2\)P\(_2\)O\(_7\) is determined by a dipole–dipole interaction. The emission intensity of Ba\(_2\)P\(_2\)O\(_7\) :Eu\(^{3+}\) was enhanced by doping charge compensation Li\(^+\), Na\(^+\) and K\(^+\). The CIE coordinates of the phosphors can be tuned from blue-green through white, to yellow and finally to orange-red with changing the Eu\(^{3+}\)/Tb\(^{3+}\) ratio. The average decay time of Eu\(^{3+}\) increases from 2.10 to 5.81 ms with the concentration of Tb\(^{3+}\) increasing from 2% to 8%, and reaches the maximum at 0.08, and is shortened when the concentration of Tb\(^{3+}\) goes beyond 8%.

1. Introduction

Nowadays, as the next-generation lighting and display systems, the white light-emitting diodes (WLEDs) are attracting much attention due to their environmental friendliness, reliability, and low power consumption.\(^{3,5,28,29}\) In general, the manufacture of white light phosphors follows one of two routes. One approach is to mix monochromatic (red/green/blue) phosphors in the best proportion, the other approach is to excite yellow phosphors using blue or ultraviolet (UV) emitting chips.\(^{6}\) However, for phosphor mixtures, the strong re-absorption and nonuniformity of luminescence problems exist, this result gives rise to the loss of luminescence efficiency, properties, and multicolor emitting points. Compared with phosphor mixtures, a single phase phosphor has more advantages and overcomes these problems. So, the single phase phosphor is a very promising material.\(^{7,9,30,31}\)

Recently, more and more scholars focus on pyrophosphate phosphor materials which have the advantage of environmental friendliness, chemical stability, low power consumption, and high efficiency, etc.\(^{19}\) In the rare earth family, due to the existence of \(5D_{4,5} \rightarrow 7F_5\) and \(5D_4 \rightarrow 7F_5\) transition, the Tb\(^{3+}\) ion doped phosphors which can emit blue and green light has been prepared in previous research. Meanwhile, Eu\(^{3+}\) ion is a red emitting activator due to its \(5D_{0,1} \rightarrow 7F_2\) transition.\(^{6}\) Accordingly, the Tb\(^{3+}\) and Eu\(^{3+}\) co-doped phosphors can generate simultaneous the red/green/blue emissions. At present, by means of the energy-transfer from a sensitizer to an activator, the multicolor emitting phosphor can be usually designed under ultraviolet excitation, so by co-doping of Eu\(^{3+}\) and Tb\(^{3+}\) ions, the color emission may be tuned base on the energy transfer from Tb\(^{3+}\) to Eu\(^{3+}\). In some literatures, the Tb\(^{3+}\) and Eu\(^{3+}\) co-doped phosphors have been used in the studies of W-LEDs, such as Sr\(_2\)P\(_2\)O\(_7\) :Tb\(^{3+}\), Eu\(^{3+}\), KCa\(_x\)(PO\(_4\))\(_y\) :Tb\(^{3+}\), Eu\(^{3+}\), \(LaPO_4 :Tb^{3+}, Eu^{3+}\), \(Bi^{3+}\).\(^{12}\)

For all we know, for Ba\(_{1-x}\) \(P_2\)O\(_7\) :xEu\(^{3+}\), yTb\(^{3+}\) phosphors, its luminescence properties and the mechanism of Eu\(^{3+}\) \(\rightarrow\) Eu\(^{3+}\) energy transfer have not been investigated in the previous study. In this study, the phosphors Ba\(_2\)P\(_2\)O\(_7\) :Tb\(^{3+}\), Eu\(^{3+}\) were synthesized by solid-state reaction method in air. The crystal structure, photoluminescence properties, color tunability, the mechanism of Tb\(^{3+}\) \(\rightarrow\) Eu\(^{3+}\) energy transfer, and luminous efficiency of prepared samples were systematically studied.

2. Experimental

2.1. Sample synthesis

The powder samples Ba\(_2\)P\(_2\)O\(_7\) :Tb\(^{3+}\), Eu\(^{3+}\) were prepared by the conventional solid-state reaction in air. According to mole ratio of elements in Ba\(_{1-x}\) \(P_2\)O\(_7\) :0.06Tb\(^{3+}\), yEu\(^{3+}\), we calculated and weighed the raw materials BaCO\(_3\) (A.R.), NH\(_4\)H\(_2\)PO\(_4\) (A.R.), Tb\(_2\)O\(_3\) (99.99%), and Eu\(_2\)O\(_3\) (99.99%), and then the raw materials were fully ground in an agate mortar. Eventually, the mixtures in the alumina crucible was put into the muffle furnace and calcined at 1100 °C for 2 h. The samples were obtained after cooled to room temperature.

2.2. Sample characterization

The X-ray diffraction (XRD) patterns of the samples were recorded via using Japan Rigaku D/Max-2200 X-ray diffractometer with Cu-K\(_\alpha\) radiation (\(\lambda = 0.15406\) nm). The excitation and emission spectra were observed by the Hitachi F-4600
fluorescence spectrophotometer. Fluorescence lifetime were investigated by using the Edinburgh FS5 fluorescence spectrophotometer. All the measurements above were carried out at room temperature.

3. Results and discussion

3.1. Structure characterization

Fig. 1a and b shows the X-ray diffraction patterns of Ba2P2O7·Tb3+, Eu3+ and Ba1.88P2O7·0.06Eu3+, 0.06M+ (Li+, Na+, K+) samples, respectively. All XRD patterns are found to agree well with standard data (JCPDS 30-0144) in the Ba2P2O7. The results indicate that the Ba2P2O7 host keep the crystal structure when the M+, Tb3+ and Eu3+ in small amount doping.

3.2. Luminescence properties of the Ba2P2O7·Tb3+, Eu3+

Fig. 2a shows the excitation and emission spectra of Ba1.94P2O7·0.06Eu3+ phosphor. When monitored at 593 nm, several excitation peaks at 361 nm, 381 nm and 395 nm are obtained assigned to 7F0 → 5D4, 7F0 → 5L4 and 7F0 → 5L6 transitions, respectively.12,13 In the emission spectrum of Ba1.94P2O7·0.06Eu3+ sample, under excitation at 395 nm, the feature emission peaks are observed at 593 and 613 nm. According to the Judd–Ofelt theory,14-16 the transition 5D0→7F1 is the magnetic dipole, and it is orange emission at 593 nm. While the transition 5D0→7F2 is the electric-dipole, it is red emission centered at 613 nm.

As we all know, the transition 5D0→7F1 (593 nm) is the magnetic dipole, and it is insensitive to distortion of the inversion symmetry, whereas the electric dipole transition 5D0→7F2 (613 nm) is hypersensitive to it, and the intensity ratio (5D0→7F2)/(5D0→7F1) suggests the degree of distortion.16 In our experiment, the transition 5D0→7F1 (593 nm) was stronger than the 5D0→7F2 (613 nm), this result reveals Eu3+ ions mainly occupy the inversion symmetry lattice site.

Fig. 2b shows the excitation and emission spectra of Ba1.94P2O7·0.06Tb3+. When monitored at 545 nm, there are several excitation peaks between 300 and 380 nm, where the strongest one is at 378 nm (7F6→5D3).6,10 In the emission spectrum of

![Figure 1](image1.png)

**Fig. 1** XRD pattern of phosphors: (a) Ba2−xP2O7·xTb3+, yEu3+, (b) Ba1.88P2O7·0.06Eu3+, 0.06M+ (Li+, Na+, K+).

![Figure 2](image2.png)

**Fig. 2** Excitation and emission spectra of phosphor: (a) Ba1.94P2O7·0.06Eu3+, (b) Ba1.94P2O7·0.06Tb3+.
Enhanced and reaches the maximum at $Tb^{3+}$ in the Ba$_2$P$_2$O$_7$, the samples exhibit not only $5D_{4}$ to $7F_{6,5,4,3}$ luminescent intensity of $Tb^{3+}$ in the presence of $Eu^{3+}$. The emission intensities of 593 and 613 nm ($5D_{0}$ of 0, 0.005, 0.015, 0.04, 0.06 and 0.08, respectively), the emission intensity of $Tb^{3+}$ is impaired. This indicated that the energy transfer from $Tb^{3+}$ to $Eu^{3+}$ is very effective.

From the emission intensity of sensitizer, the energy-transfer efficiency ($\eta_{ET}$) from a sensitizer to an activator can be obtained as the following equation:\textsuperscript{8,9}

$$\eta_{ET} = 1 - \frac{I_s}{I_{s0}} \quad (1)$$

where $I_{s0}$ is the intrinsic luminescent intensity of $Tb^{3+}$, $I_s$ is the luminescent intensity of $Tb^{3+}$ in the presence of $Eu^{3+}$. The energy transfer efficiencies from $Tb^{3+}$ to $Eu^{3+}$ excited at 378 nm are illustrated in Fig. 4. As a result, the energy transfer efficiency values from $Tb^{3+}$ to $Eu^{3+}$ were calculated to be 70%, 77.91%, 79.82%, 81.26%, and 79.07% for Ba$_{1.94}$P$_2$O$_7$·0.06$Tb^{3+}$, 0.06$Eu^{3+}$, which shows the strongest emission.

In general, for the energy transfer from a sensitizer to an activator, there are two main aspects: one is exchange interaction (the typical critical distance is no more than 5 Å) and the other is multipolar interaction (the critical distance is longer than 10 Å).\textsuperscript{17,23,24} According to Blasse, the critical distance $R_c$ for energy transfer from the $Tb^{3+}$ to $Eu^{3+}$ ions can be calculated using the following equation: \textsuperscript{18,20,26,27}

$$R_c = \frac{2V}{3\pi x_c N} \left( \frac{3}{4\pi N} \right)^{1/3} \quad (2)$$

herein, $V$ is the unit cell volume, $x_c$ is the critical concentration, and $N$ is the coordinate number of molecules in the unit cell. For the Ba$_2$P$_2$O$_7$ host, $V = 543.87$ Å$^3$, $N = 3$, and $x_c = 0.065$ (total concentration of $Tb^{3+}$ and $Eu^{3+}$ when the $Tb^{3+}$ emission intensity is half of that in the absence of $Eu^{3+}$). According to the above equation, the value of $R_c$ is 17.47 Å, and it is much larger than 5 Å. So the energy transfer from $Tb^{3+}$ to $Eu^{3+}$ ions happen in the way of electric multipolar interaction for this system.

In order to further verify the mechanism of energy transfer for Ba$_2$P$_2$O$_7$:$Tb^{3+}$, $Eu^{3+}$, Dexter’s formula of multipolar interaction and Reisfeld’s approximation are used as follows:\textsuperscript{19,21,22}

$$\frac{I_0}{I_s} \propto C_n^{6/3} \quad (3)$$

herein, the $C$ is the $Eu^{3+}$ concentration, $I_s$ is the luminescent intensity of $Tb^{3+}$ in Ba$_2$P$_2$O$_7$:$Tb^{3+}$, $Eu^{3+}$, and $I_{s0}$ is the intrinsic luminescent intensity of Ba$_2$P$_2$O$_7$:$Tb^{3+}$. Based on the eqn (3), when $n = 6, 8, 10$ correspond to dipole–dipole, dipole–quadrupole and quadrupole–quadrupole interactions, respectively.

The $I_{s0}/I_s$~$C_n^{6/3}$ ($n = 6, 8, 10$) plots for Ba$_{1.94-y}$P$_2$O$_7$·0.06$Tb^{3+}$, $y$Eu$^{3+}$ (at excitation wavelength of 378 nm and emission wavelength of 545 nm) are shown in Fig. 5. It can be seen that when $n = 6$, the $I_{s0}/I_s$ value follows the linear growth law much better than $n = 8$ or 10. So the dipole–dipole mechanism is the mainly way for the energy transfer between $Tb^{3+}$ and $Eu^{3+}$ in Ba$_2$P$_2$O$_7$.

The energy-transfer mechanism of $Eu^{3+}$ and $Eu^{3+}$ are shown in Fig. 6. Upon 378 nm excitation, few excited $Tb^{3+}$ ions is excited to higher energy level through $Tb^{3+}$:$F_{6}$-$D_{4}$ transitions, then relaxed to lower energy levels through $Tb^{3+}$:$D_{6}$-$F_{5,4,3}$ non-radiative transitions and to its lower lying $Tb^{3+}$:$D_{4}$ metastable state relaxed to lower energy levels through $Tb^{3+}$:$F_{5,4,3}$ transitions.

The rest of the $Tb^{3+}$:$D_{4}$ level transfer their energy to the $Eu^{3+}$:$G_{2}$ level i.e. the energy transfer. A fast non-radiative decay
from $^5\text{G}_2$ excited state increase the population of $^5\text{D}_0$ metastable state causing enhanced emission from Eu$^{3+}$ ions through $^5\text{D}_0\rightarrow^7\text{F}_J$ ($J = 0$–6) transitions. Finally, the characteristic emission of Eu$^{3+}$ at 593 and 613 nm was enhanced.

Fig. 7 shows luminescence decay for $^5\text{D}_0$ level of Eu$^{3+}$ in Ba$_{1.94}$P$_2$O$_7$:0.06Eu$^{3+}$, yTb$^{3+}$ (y = 2%, 4%, 8%, 10%) excited at 378 nm and measured at 593 nm. The decay times of Eu$^{3+}$ can be more accurate fitted via using second-order exponential decay mode as follows:

$$I = A_1 \exp \left(-\frac{t}{\tau_1}\right) + A_2 \exp \left(-\frac{t}{\tau_2}\right)$$

(4)

where $A_1$ and $A_2$ are the fitting parameters, $t$ is the time, $\tau_1$ and $\tau_2$ are the decay times for different exponential components, $I$ is the phosphorescent intensity, respectively. The average decay time $\tau$ of Eu$^{3+}$ can be expressed as the following equation:

$$\tau = \frac{A_1 \tau_1^2 + A_2 \tau_2^2}{A_1 \tau_1 + A_2 \tau_2}$$

(5)

For Ba$_{1.94}$P$_2$O$_7$:0.06Eu$^{3+}$, yTb$^{3+}$ (y = 0.02, 0.04, 0.08, 0.10) phosphors, corresponding to the $^5\text{D}_0$ level of Eu$^{3+}$, when the samples are excited at 378 nm, the average lifetimes that calculated by eqn (5) are 2.10, 2.51, 5.81, and 2.65 ms, respectively. The average decay time of Eu$^{3+}$ increases from 2.10 to 5.81 ms as the increase of the concentration of Tb$^{3+}$ from 0.02 to 0.08, the results confirmed the exist of energy transfer from Tb$^{3+}$ to Eu$^{3+}$ ions. When the Tb$^{3+}$ beyond 8% mol, the average decay time of Eu$^{3+}$ is shortened oppositely, which is corresponding to the widely known concentration quenching effect happened in high concentration.

Due to Eu$^{3+}$ and Ba$^{2+}$ have similar radius, the Eu enter the lattice, and replace the position of the Ba$^{2+}$ to form a point defect Eu$^{3+}_{\text{Ba}}$ which have a positive charge. In order to keep the charge balance, it can be implemented by doping alkali metal ions. For Ba$_{1.94}$P$_2$O$_7$:0.06Eu$^{3+}$ phosphors, we regard Li$^+$ (Li$_2$CO$_3$), Na$^+$ (Na$_2$CO$_3$) and K$^+$ (K$_2$CO$_3$) as charge compensations to stabilize the structure. The results are shown in Fig. 8.
When the \( M^+ (\text{Li}^+, \text{Na}^+, \text{K}^+) \) doping concentration are 0.06 respectively, the intensity of \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) are all enhanced. The doping \( \text{Na}^+ \) enhanced emission intensity more than by doping \( \text{Li}^+ \) or \( \text{K}^+ \) at 593 nm, and the emission intensity at 613 nm is higher by doping \( \text{K}^+ \).

Fig. 9 shows the CIE chromaticity diagram for \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) phosphors. According to the emission spectra, the values of CIE parameters of the \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) phosphors with different doping concentrations are summarized in Table 1. Under the excitation at 378 nm, the CIE coordinates of the phosphors can be tuned from blue-green (point a1, a2, a3, a4) to white (point a5), yellow (point a6, a7, a8, a9) and finally to the orange-red (point a10, a11) by changing the \( \text{Eu}^{3+}/\text{Tb}^{3+} \) ratio. The CIE chromaticity coordinates associated with white luminescence (0.358, 0.305) of \( \text{Ba}_{1.94-x} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) sample (point a5) are very close to an ideal white chromaticity coordinates (0.33, 0.33). However, upon 395 nm excitation, the CIE chromaticity coordinates are associated with orange-red luminescence of \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) phosphor (point a10, a11). Above results indicate that the phosphors show merits of multicolor emissions in the visible region when excited by a single wavelength light.

4. Conclusion

In summary, the \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) phosphors were synthesized by a solid-state reaction at 1100 °C for 2 h. The \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) phosphors can be effectively excited at 378 nm and have several emission peaks centered at 545 nm, 593 nm and 613 nm. The CIE coordinates of the phosphors can be tuned from blue-green to white, yellow and finally to the orange-red by changing the \( \text{Eu}^{3+}/\text{Tb}^{3+} \) ratio. The emission intensity of \( \text{Ba}_{2-x-y} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \) was enhanced by doping charge compensation \( M^+ (\text{Li}^+, \text{Na}^+, \text{K}^+) \). The energy transfer from \( \text{Tb}^{3+} \) to \( \text{Eu}^{3+} \) in \( \text{Ba}_2\text{P}_2\text{O}_7 \) was demonstrated to be dipole–dipole interaction mechanism. The energy transfer efficiency in \( \text{Tb}^{3+}–\text{Eu}^{3+} \) was approximately 81.26% at \( x = 0.06, y = 0.06 \), and for the \( \text{Ba}_{1.94-x} \text{P}_2\text{O}_7:0.06\text{Eu}^{3+} \), \( y\text{Tb}^{3+} \) (\( y = 0.02, 0.04, 0.08, 0.10 \)) phosphors, under excitation at 378 nm, the average lifetimes of \( \text{Eu}^{3+} \) were determined to be 2.10, 2.51, 5.81, and 2.65 ms, respectively.

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References