

## *Appendices*

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## APPENDIX I

### Historical Note on Phosphor Recipes

The word phosphorus derives from the Greek  $\phi\omega\sigma\phi\omicron\rho\omicron\varsigma$  [*fosforos*], combining  $\phi\omega\varsigma$  (light) and  $\phi\epsilon\rho\omega$  (to carry), and meaning light carrying or luminous. Initially, the assignation of this word was given to any substance that evinced the property of phosphorescence. The term phosphorescence was, for a time, used to describe the emission of diffuse light from causes other than combustion; this word was used more specifically to describe substances which became luminous following exposure to light excitation. These developments and observations had their origin in alchemical attempts to manufacture noble metals through use of the evasive Philosopher's Stone. The element phosphorus (P) was discovered in such a search by Henning Brand (1669) while experimenting with concentrated urine; distillation resulted in a white substance that gave out enough light to allow Brand to read in the dark. This phosphorescence property lent its name to the element (Figure 1).<sup>1</sup>



**Figure 1** Depiction of the discovery of phosphorus by Brand as perceived by Joseph Wright of Derby some years later (Copyright by Derby City Council Art Galleries, permission pending).

Historically, there is documented evidence that phosphors have been produced and put to use as early as 2000 years ago as is recorded in a Chinese text (Figure 2). The phosphors described were of the persistent type and were used in a painting which glowed in the dark and was considered to some to have inexplicable magic. The methods for preparing the phosphors or the phosphors used in these paintings apparently were obtained from Japan where raw materials, such as calcium from seashells and sulfur from volcanic activity, used for the synthesis of sulfide phosphors occur naturally. The page describing the phosphorescent painting is shown in Figure 2, courtesy of Dr. M. Tamatani.<sup>2</sup> (A translation of the Chinese text, kindly provided by Professor Y. Zhao, is given in the caption.)



**Figure 2** Copy of the Chinese text describing the acquisition of a luminescent painting by Xu Zhi-e written for a compilation of historical and folk tales published in the Song dynasty (960–1279 A.D.) by Wen Ying. In the text, reference is made to a book published in the reign of Han Wu Di (140–88 B.C.) which would indicate that man-made phosphors have been available for more than 2000 years. Some questions have been raised as to the accuracy of the compilations, *Xiang-shan Ye Lu*, from which this passage is taken; regardless, it is apparent that phosphorescent materials have been around for some time. The Chinese written text reads as follows (right to left):

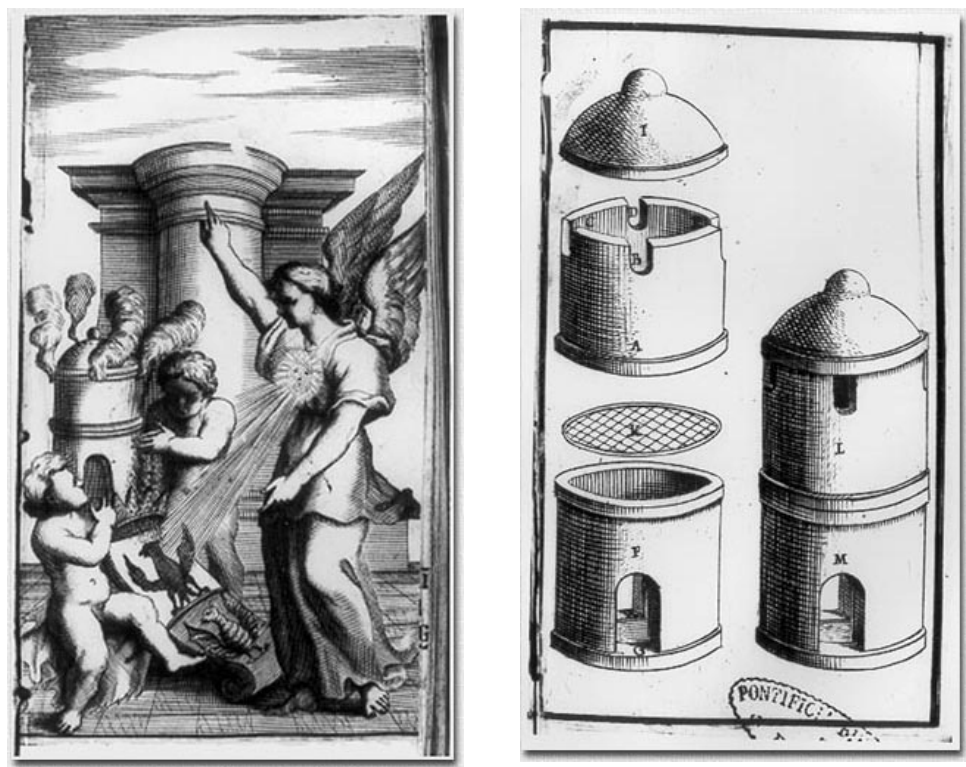
Xu Zhi-e, born South of the Yangtze River, was the youngest son of the governor of Xu Wen, of Run Zhou. He was fond of collecting rare antiques and other curios. On one occasion, he spent five hundred thousand in cash to acquire the head of a phoenix complete with a shining and colorful skeleton. The head possessed a red crest and a golden beak which vividly resembled those of a real rooster; it was five inches wide and the back of the head was flat, like a pillar. He acquired at the same time a painting of a cow; the painting when viewed in daylight showed the cow grazing outside an open pen; however, when viewed in the dark, the picture showed the cow resting inside the barn. Xu presented the painting to his sovereign, Li Yu, the last emperor of the Southern Tang Dynasty. Following the fall of the Tang Dynasty, the painting eventually passed to Tai Zong, the second emperor of the Song Dynasty. Tai Zong showed this painting to all his Ministers; none of them could explain the secret of the phenomena except for an officer in charge of religious matters named Zhan Nin. He explained that at low tide in the China Sea, southern people (Japanese) frequented the beaches to harvest nacre. Often they found that these shells contained a special liquid which when collected and mixed with paint formed a special type of ink. Writings or paintings using this ink had the properties of vanishing in daylight and becoming visible in the dark. He added that in the sea shores of the land of southern people (Japan) sometimes strong winds would grind these rocks with water to form a similar paint. All the court officials thought the Ning's explanation was nonsense; he claimed that he had obtained his information from a book, *Hai Wai Yi Ji* written by Zhang Qian, the famous envoy sent to the Western regions by Han Wu Di. Later, a scholar named Du Gao, who consulted some imperial collections, found the reference in a work dating back to the Six Dynasties (220–586 A.D.).

The denomination of phosphor (*phosphori*) first appeared in the seventeenth century in connection with the discovery of the Bolognian Stone (BaS) by Vincenzo Casciarolo in 1602.<sup>3</sup> The base material ( $\text{BaSO}_4$ , barite) is found near Monte Paderno as scattered stones; when properly treated it gave rise to a reddish glow which led to the scientific study of luminescent objects. There was considerable interest throughout Italy in these materials and attempts were made to use it as the Philosopher's Stone (i.e., as the catalyst for the conversion of ignoble to noble metals). Cesare La Galla described the properties of the stone in *De Phenomenis in Orbe Lunae* published in 1612; he was the first to point out that phosphorescence only occurred after calcinations and he tried to explain the phenomena as due to the slow release of fire and/or light trapped in the material during exposure. The method for preparation of the Bolognian Stone was described in detail by Pierre Potier in *Pharmacopea Spagirica* in 1625; the stone was of interest to pharmacologists because it reputedly also possessed depilatory properties. Potier's recipe is likely the first phosphor recipe on record, though published in Latin. As quoted by E.N. Harvey,<sup>4</sup> it reads:

According to the light-bearing quality sought for, it ( $\text{BaSO}_4$ ) is calcinated in two ways. The first is to reduce the stone to very fine meal, then to calcinate it in a crucible with very strong fire. The second is to reduce it to a meal and, in the place of thalerum (?), work it into cake either with water or the white of an egg. After they have dried out they are put in layers with coal in a blast furnace and, after a very hot fire has been made, they are calcinated for four or five hours. When the oven has cooled off the cakes are taken out. If not cooked sufficiently the procedure is repeated as before. Sometimes this is done three times. The best calcinations results when stones, shining, pure and diaphanous are used. From this powder various animals are formed in little boxes (pyxidiculum) which shine wonderfully in the dark.

Preliminary scientific investigations of the properties of this stone were discussed in *De Illuminabili Lapide Bononiensi Epistola* by Ovidio Montalbani and in *Litheosphorus Sive De Lapide Boboniensi* by Fortinius Licetus in 1634 and 1640, respectively; both authors were professors at the famed University of Bologna. In his book, Montalbani described the various colors of light that could be obtained from the stone as a function of preparation and first suggested an analogy between the phosphorescence and burning. Licetus, on the other hand, related in some detail the history of the stone and various attempts by the learned community in Bologna to explain the origin of the emitted light. Licetus postulated, for example, that the faint light of a new moon was produced by lunar material similar to the Bolognian Stone; this suggestion led to controversy on the source of this radiation with no lesser a luminary than Galileo Galilei. Of course, Galileo was right and the diffuse light observed in that lunar phase is due to sunlight reflected from Earth.<sup>5</sup>

The properties of the phosphorescent stone attracted attention throughout the Italian peninsula and the European continent and led to much speculation as to the origin of the emission. One popular belief advanced by Athanasius Kircher of Fulda (Hesse) was that the phosphorus attracted light much as a magnet attracted iron filings. Calcination was thought to produce pores in the stone; these pores then held air suffused with light whose gradual release led to the observed phosphorescence. The experiments leading to this conclusion are detailed in *Ars Magna Lucis Et Umbra*, published in 1646. News regarding the unusual properties of the *lapide Bononiensi* was carried to the British Isles by John Evelyn (1620–1706) following a visit to Bologna in 1645;<sup>6</sup> he reported that the recipe for the preparation of the stone had been lost by then and he apparently had not been aware of Potier's pharmacological work.



**Figure 3** (left). An illustration by Marc'Antonio Cellio allegorizing the magical phosphorescent qualities of the Bologna Stone produced in the course of calcinations. (right). Drawing of the furnace used by Casciarolo for calcinations of  $\text{BaSO}_4$  (barite) to produce his magical stone. Note that the structure of this furnace is not much different than modern ovens used for similar purposes. These drawings appeared in *Il Fosforo o vero la Pietra Bolognese*, published in 1680 by Cellio and are reproduced from Ref. 3; this volume is in the University Library of Bologna.

The interest in light-emitting materials led to the invention and synthesis of three other phosphori of interest to the scientific and/or the alchemical communities of that period. The first one was due to Christian Adolph Balduin (1632–1682) who in 1675 prepared a phosphorescent form of calcium nitrate by mixing chalk and nitric acid and distilling the solution to dryness. When calcium nitrate is overheated it develops a yellowish tint and emits a reddish phosphorescence in the dark following exposure to sunlight. This compound is hygroscopic and turns to a liquid when exposed to atmosphere; he believed that the solution formed in this way represented a *spiritus mundi* and it is likely that the paint used in the Chinese paintings mentioned above was a solution of this type. Because the material needed to be kept in a sealed vessel, Balduin called his material *phosphorus hermeticus* and disclosed his results in *Aurum Superius et Inferius Aurae Superioris et Inferioris Hermeticum* which appeared simultaneously in Amsterdam and in Frankfurt in 1675. Balduin communicated his results to the Royal Society of London in 1676 and as a consequence was elected to Fellowship of the Society. His phosphor was henceforth named Balduin's phosphorus.

The second material is known as Homberg's phosphorus named after Wilhelm Homberg (1652–1715) who made notable contributions to the foundation of modern chemistry and who had an interest in the photochromic properties of silver nitrate. In the course of his

experimentations, Homberg synthesized calcium chloride sometime in the 1690's and showed it had phosphorescence properties.<sup>7</sup>

John Canton (1718–1772), a man born under modest circumstances, had a wide ranging set of scientific interests including electricity, magnetism, and optics. He showed, for example, that clouds were electrified both positively and negatively and designed experimental methods that are (even now) used to determine the sign of charges via induction. He was awarded the Copley Medal of the Royal Society twice, in 1751 for making artificial magnets and in 1765 for measuring the compressibility of water. In 1768, he reported in *Philosophical Transactions* the discovery of a strong phosphorescent material which was promptly named Canton's phosphorus (CaS).<sup>8</sup> His report is the earliest recipe of any phosphor written in English; Joseph Priestly cites Canton in *The History and Present State of Discoveries Relating to Vision, Light and Colours*, published in London in 1772. Priestly writes (pages 370–372):<sup>9</sup>

In the next place I shall present my reader with an account of this composition of Mr. Canton's which makes an artificial phosphorus greatly superior to any single natural substance, and has the advantage of being easily and cheaply prepared; by which means it is now in every person's power to amuse himself and his friends with these curious experiments. His receipt for making it is as follows:

"Calcinate some common oyster shells, by keeping them in a good coal fire for half an hour, and let the purest part of the calx be pulverized and sifted. Mix with three parts of this powder one part of flowers of sulphur; let this mixture be rammed in a crucible, of about an inch and a half depth, till it be almost full, and let it be placed in the middle of the fire, where it must be kept red hot, for one hour at least, and then be set by to cool. When it is cold, turn it out of the crucible, and cutting, or breaking to pieces, scrape off, upon trial, the brightest pieces; which, if good phosphorus, will be a white powder, and may be preserved by keeping it in a dry phial with a ground stopple."

We note, of course, though the language in the recipe is a bit arcane, the method described is not much different than some of those presented in Section 2 of this work.

Beginning with the discovery of the Bolognian Stone, the phenomena of and the origin of the observed phosphorescence were sources of much interest, fascination, and speculation. In addition to Kircher's conjecture as to the source of the light noted above, others such as Giullio Cesare La Galla (1576–1624) of Rome speculated that the emissions were due to the slow release of fire and light trapped in the stone in the process of calcinations, much as a sponge would absorb water and then release it as it is squeezed. He attributed this explanation to Galileo Galilei (1564–1642) himself. In 1652, another Professor from Rome, Nicola Zucchi (1586–1670), reported that the intensity of the phosphorescence emitted from the stone was proportional to the intensity of the excitation light and that the color of the light emitted was independent of the coloration of the excitation light. These conclusions were reaffirmed in 1728 by Francesco Zanotti who also asserted that the light, rather than being attracted like a sponge or magnet to the stone, emanated the radiation on its own. The idea of the Bolognian Stone attracting light and causing the phosphorescence either by reemitting the light or by reflecting it, however, persisted well into the nineteenth century.<sup>3</sup>

The beginning of modern studies of phosphor synthesis can be attributed to a French chemist, Theodore Sidot, who in 1866 was able to grow small ZnS crystals using sublimation. Although Sidot's original purpose was to study crystal growth, he found that his crystals phosphoresced in the dark; the synthesis methods and experimental results were reported to the French Academy by Edmond Becquerel in a note in 1866 and the material

was named Sidot's blende.<sup>10</sup> About this time, Becquerel published his opus on light, *La Lumiere-Ses Causes et Ses Effects* (1867);<sup>11</sup> perhaps due to his involvement in the discovery of Sidot's blende, Becquerel discusses at length the phosphorescence of various compounds including ruby ( $\text{Al}_2\text{O}_3\cdot\text{Cr}^{3+}$ ). He believed that in the latter case the luminescence observed in this gem was an intrinsic property of alumina and that Cr simply played a role as an activator. This led to a long-lasting controversy with Lecoq de Boisbaudran who proved to be correct in proposing that the R-line fluorescence arose due to the presence of chromium.<sup>12</sup> Results of studies by V. Klatt and Philip Leonard also showed that the phosphorescence properties of CaS and other phosphors depended on the presence of metal contaminants; the emission from Sidot's blende, for example, is due to trace amounts of copper.<sup>13</sup>

In the late 1800's, the terminology describing phosphorescent phenomena was revised. The word phosphor began to be applied in a more limited sense (i.e., only to those materials which become self-luminous after exposure to light); as of late, the word phosphor is used to describe principally solid luminescent inorganic materials. The technical differences between fluorescence and phosphorescence were resolved following the introduction in 1888 of the word luminescence by Eilhardt Wiedemann in chemical processes;<sup>14</sup> the word luminescence is used to describe most light emission processes following some form of excitation. Phosphorescence and fluorescence are, however, still in use to categorize long- and short-lived luminescent emissions, respectively.

Philip E.A. Lenard and his co-workers helped to establish phosphor research on a firm scientific footing at the turn of the nineteenth and the beginning of the twentieth century. He was able to synthesize not only Sidot's blende but also a series of alkaline earth chalcogenides (sulfides and selenides) and demonstrated that the light emission of the compounds could be altered by introducing metallic ions into the materials. The latter ions form diverse centers in the material and are said to activate the luminescence; hence they were named activator ions. Because of his extensive work on phosphors detailed in a *Handbuch* article, alkaline chalcogenide phosphors are called Lenard phosphors.<sup>15</sup>

Because of the necessity for better phosphors for the display industries in the late 1940's and early 1950's, considerable work took place at the Radio Corporation of America (RCA). One of the principals there was Humboldt Leverenz who developed synthesized and investigated the properties of many the luminescent materials that are even now in use. In 1950, he published *An Introduction to Luminescence in Solids* in which he summarized much of his life's work; for many years this work was accepted as the standard text in the phosphor art and material in the book remains useful even today.<sup>16</sup>

Because of the advent of atomic and quantum physics and chemistry and the work of many researchers in this area of inquiry which preceded us, we have now a much better understanding as to the mechanisms which produce luminescence in solids and we are almost to the point where we can begin thinking in terms of designing and tailoring materials to our specific technical needs. The *Phosphor Handbook* contains an updated discussion of modern synthesis methods as well as the description of phosphors suitable for a variety of technical purposes. It is our hope that the present volume serves to complement the information found in that handbook.

## References

1. Weeks, M.E., *Discovery of the elements*, J. Chem. Educ., pp. 110–130 (1968); van der Krogt, P., *Elementymology & Elements Multidict: Phosphors* (2003), ([http://www.vanderkrogt.net/elements/chronology\\_index.html](http://www.vanderkrogt.net/elements/chronology_index.html)).

2. Nakajima, S., and Tamitani, M., History of phosphors technology, in *Phosphor Handbook*, Eds. Shionoya, S., and Yen, W.M., CRC Press, Boca Raton, FL, p. 898, (1998).
3. Roda, A., The discovery of luminescence: the Bolognian Stone, in *Bioluminescence and Chemiluminescence: Perspectives for the 21<sup>st</sup> Century*, Eds. Roda, A., Pazzagli, M., Kricka, L.J., and Stanley, P.E., John Wiley & Sons, New York (1998).
4. Harvey, E.N., *A History of Luminescence*, American Philosophical Society, Philadelphia (1957).
5. The various antique volumes cited are in depository at the University Library of Bologna, Italy.
6. John Evelyn is a famed seventeenth century chronicler and diarist who traveled extensively in Europe in the early 1600's; he is also known for his books on flora and gardening. He was one of the principals in establishing the Royal Society, and subsequently the Philosophical Transactions of the Royal Society in 1665. Accounts of his visit to Bologna in 1644–1645 appear in the inaugural volumes of the transactions and are also found in editions of his dairies: for example, Evelyn, John, *Dairy of John Evelyn*, J.M. Dent & Sons, London (1973).
7. Jensen, W.B., Whatever happened to Wilhem Homberg?, *Bull. Hist. Chem.*, 3, 21–24 (1989).
8. Canton, J., *Complete Works*, AIM25: Royal Society: Canton, John (1718–1772), (2003) (<<http://www.aim25.ac.uk/>>).
9. I am grateful to Dr. Guy Hill for contributing this citation.
10. Becquerel, E., *Compt. Rend. Acad. Sci.*, 63, 188 (1866).
11. Becquerel, E., *La Luminiere-Ses Causes et ses Effets*, Librairie de Firmin Didot Freres, Fils et Cie, Paris, Chapter 4, (1867)
12. de Boisbaudran, Lecoq, *Compt. Rend. Acad. Sci.*, 103, 1107 (1886).
13. Klatt, V., and Lenard, Ph., *Wied. Ann.*, 38, 90 (1889).
14. Wiedemann, E., *Ann. Phys. Chem.*, 34, 46 (1888).
15. Lenard, P.E.A., Schmidt, F., and Tomaschek, R., Phosphoreszenz und Fluoreszenz, in *Handbuch der Experimentalphysik*, Vol. 23, Akademie Verlagsgesellschaft, Leipzig (1928).
16. Leverenz, H.W., *An Introduction to Luminescence of Solids*, John Wiley & Sons, New York (1950).

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## APPENDIX II

### Phosphor Materials Arranged in Order of Emission Wavelength

The phosphors and scintillators in Sections 4, 7, and 8 are listed in order of increasing wavelength of the maximum emission.

Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
220, 310	BaF <sub>2</sub>	337	$\alpha$ -Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Pb <sup>2+</sup>
233	CaSO <sub>4</sub> :Pb <sup>2+</sup>	338	(CeMg)SrAl <sub>11</sub> O <sub>18</sub> :Ce
254	BaMgAl <sub>10</sub> O <sub>17</sub> :Ce <sup>3+</sup>	342–347	(CeMg)BaAl <sub>11</sub> O <sub>18</sub> :Ce
254	YAlO <sub>3</sub> :Ce <sup>3+</sup>	347, 388	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Ce <sup>3+</sup>
267	MgSO <sub>4</sub> :Pb <sup>2+</sup>	348	LaOCl:Bi <sup>3+</sup>
280, 355	Ca <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub> :2%Ce <sup>3+</sup>	348, 370	LaSiO <sub>3</sub> Cl:Ce <sup>3+</sup>
288	Ca <sub>2</sub> B <sub>5</sub> O <sub>9</sub> Cl:Pb <sup>2+</sup>	350	BaSi <sub>2</sub> O <sub>5</sub> :Pb <sup>2+</sup>
295	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Bi <sup>3+</sup>	350	YAlO <sub>3</sub> :Ce <sup>3+</sup>
300, 370, 400, 460	LaOBr:Tm <sup>3+</sup>	350, 575	$\beta$ -Ca <sub>2</sub> P <sub>2</sub> O <sub>7</sub> :Sn,Mn
302, 319	BaSO <sub>4</sub> :Ce <sup>3+</sup>	351	BaSi <sub>2</sub> O <sub>5</sub> :Pb
302, 319	SrSO <sub>4</sub> :Ce <sup>3+</sup>	352, 371	$\alpha$ -Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Ce <sup>3+</sup>
303	$\beta$ -SrO·3B <sub>2</sub> O <sub>3</sub> :Pb <sup>2+</sup>	358–385	LaBr <sub>3</sub> :Ce <sup>3+</sup>
305	CeF <sub>3</sub>	359	MgBa(SO <sub>4</sub> ) <sub>2</sub> :Eu <sup>2+</sup>
307	MgSrAl <sub>10</sub> O <sub>17</sub> :Ce	359, 636	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Sn <sup>2+</sup>
309, 327	CaSO <sub>4</sub> :Ce <sup>3+</sup>	360	Ca <sub>3</sub> Si <sub>4</sub> O <sub>4</sub> Cl <sub>2</sub> :Pb <sup>2+</sup>
310	SrB <sub>4</sub> O <sub>7</sub> :Pb <sup>2+</sup>	360, 660	$\beta$ -Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Ce <sup>3+</sup>
314	CaO:Cd <sup>2+</sup>	362	CaO:Pb <sup>2+</sup>
315	CsI	363	KMgF <sub>3</sub> :Eu <sup>2+</sup>
315	LuTaO <sub>4</sub> :Nb <sup>5+</sup>	363, 413	CaSiO <sub>3</sub> :Ce <sup>3+</sup>
319	CaSr <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> :Bi <sup>3+</sup>	365	LuAlO <sub>3</sub> :Ce <sup>3+</sup>
320	$\alpha$ -Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Tl <sup>+</sup>	366	CaS:Pb <sup>2+</sup>
320, 337	CaF <sub>2</sub> :Ce <sup>3+</sup>	366	CaS:Pb <sup>2+</sup> , Cl
320, 344	Ca <sub>2</sub> P <sub>2</sub> O <sub>7</sub> :Ce <sup>3+</sup>	368	SrO·3B <sub>2</sub> O <sub>3</sub> :Eu <sup>2+</sup> , Cl
320, 345	LaPO <sub>4</sub> :Ce <sup>3+</sup>	370	Sr <sub>w</sub> F <sub>x</sub> B <sub>4</sub> O <sub>6.5</sub> :Eu <sup>2+</sup>
325	CaB <sub>2</sub> O <sub>4</sub> :Pb <sup>2+</sup>	370	SrB <sub>4</sub> O <sub>7</sub> :Eu <sup>2+</sup> (F, Cl, Br)
330	YTaO <sub>4</sub>	370	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Eu <sup>3+</sup> , Cr <sup>3+</sup>
330–352	LaCl <sub>3</sub> :Ce <sup>3+</sup>	371	SrB <sub>4</sub> O <sub>7</sub> :Eu
333	CaO:Zn <sup>2+</sup>	375	MgSO <sub>4</sub> :Eu <sup>2+</sup>
334, 355	YPO <sub>4</sub> :Ce <sup>3+</sup>	375	Y <sub>2</sub> O <sub>3</sub> :Ce <sup>3+</sup> in SiO <sub>2</sub>
335	CaSiO <sub>3</sub> :Pb <sup>2+</sup>	376	BaSO <sub>4</sub> :Eu <sup>2+</sup>
		376	SrSO <sub>4</sub> :Eu <sup>2+</sup>

*continued*

Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
378	$\beta\text{-Sr}_3(\text{PO}_4)_2\text{:Sn}^{2+}$	410	$\text{MgBaP}_2\text{O}_7\text{:Eu}^{2+}$
380	$\text{BaFCl:Eu}^{2+}$	410	$\text{YTao}_4\text{:Nb}^{5+}$
380	$\text{Lu}_2\text{Si}_2\text{O}_7\text{:Ce}^{3+}$	410, 610	$\text{BaMg}_3\text{F}_8\text{:Eu}^{2+}, \text{Mn}^{2+}$
380, 415,		411	$\text{YOCl:Ce}^{3+}$
440, 540	$\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_2\text{O}_{10}\text{:Tb}^{3+}$	411	$\text{Zn}_2\text{SiO}_4\text{:Ti}^{4+}$
385	$\text{BaFBr:Eu}^{2+}$	412	$\beta\text{-Ca}_3(\text{PO}_4)_2\text{:Eu}^{2+}$
385	$\text{BaFCl:Eu}^{2+}, \text{Pb}^{2+}$	412, 660	$\beta\text{-Ca}_3(\text{PO}_4)_2\text{:Eu}^{2+}, \text{Mn}^{2+}$
385	$\text{Ca}_2\text{MgSi}_2\text{O}_7\text{:Ce}^{3+}$	413	$\text{Ca}_5(\text{PO}_4)_3\text{F:Sn}^{2+}$
385, 410,		413	$\text{CaYBO}_4\text{:Bi}^{3+}$
440	$\text{LaOBr:Tb}^{3+}$	413, 528	$\text{Y}_2\text{O}_3\text{:Bi}^{3+}$
385, 413	$\text{YBO}_3\text{:Ce}^{3+}$	414–626	$\text{YOF:Tb}^{3+}$
386	$\text{Mg}_2\text{Sr}(\text{SO}_4)_3\text{:Eu}^{2+}$	415	$\text{Ba}_2\text{Mg}_3\text{F}_{10}\text{:Eu}^{2+}$
388	$\text{CaSO}_4\text{:Eu}^{2+}$	415	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}\text{:Eu}^{2+}$
388	$\text{ZnO:Al}^{3+}, \text{Ga}^{3+}$	415	$\text{Lu}_{1-x}\text{Y}_x\text{AlO}_3\text{:Ce}^{3+}$
388	$\text{ZnO:Ga}^{3+}$	415	$\text{NaI:Tl}$
388, 512	$\text{CaSO}_4\text{:Eu}^{2+}, \text{Mn}^{2+}$	415	$\text{Y}_2\text{SiO}_5\text{:Ce}^{3+}$
390	$\text{CsF}$	415	$\text{YPO}_4\text{:V}^{5+}$
390	$\text{MgSrP}_2\text{O}_7\text{:Eu}^{2+}$	416	$\text{Ca}_2\text{P}_2\text{O}_7\text{:Eu}^{2+}$
390	$\text{ZnO:Ga}$	416, 643	$\text{Ca}_2\text{P}_2\text{O}_7\text{:Eu}^{2+}, \text{Mn}^{2+}$
391	$\text{Ca}_2\text{MgSi}_2\text{O}_7$	418	$\text{CaCl}_2\text{:Eu}^{2+}$ in $\text{SiO}_2$
391	$\text{CaO:Bi}^{3+}$	418–420	MSL
394	$\text{BaF}_2\text{:Eu}^{2+}$	420	$\text{CaWO}_4$
395	$\text{KAl}_{11}\text{O}_{17}\text{:Tl}^+$	420	$\text{CaWO}_4\text{:W}$
400	$\text{BaB}_8\text{O}_{13}\text{:Eu}^{2+}$	420	$\text{CsI:Na}^+$
400	$\text{BaMg}_2\text{Si}_2\text{O}_7\text{:Eu}^{2+}$	420	$\text{Lu}_2\text{SiO}_5\text{:Ce}^{3+}$
400	$\text{Zn}_2\text{SiO}_4\text{:Ti}$	420	$\text{Sr}_2\text{P}_2\text{O}_7\text{:Eu}^{2+}$
400, 525	P46 (70%) + P47 (30%)	420	$\text{SrF}_2\text{:Eu}^{2+}$
403	$\text{CaB}_2\text{P}_2\text{O}_9\text{:Eu}^{2+}$	422	$\beta\text{-Sr}_3(\text{PO}_4)_2\text{:Eu}^{2+}$
405	$\text{Mg}_2\text{Ca}(\text{SO}_4)_3\text{:Eu}^{2+}$	423	$\text{CaF}_2\text{:Eu}^{2+}$
405	$\text{SrCl}_2\text{:Eu}^{2+}$ in $\text{SiO}_2$	423	$\text{CaSiO}_3\text{:Eu}^{2+}$
405, 617	$\text{Mg}_2\text{Ca}(\text{SO}_4)_3\text{:Eu}^{2+}, \text{Mn}^{2+}$	423	$\text{CaSiO}_3\text{:Ti}^{4+}$
405, 620	$\text{MgBaP}_2\text{O}_7\text{:Eu}^{2+}, \text{Mn}^{2+}$	425	$\beta\text{-Sr}_3(\text{PO}_4)_2\text{:Eu}^{2+}$
405–432	$\text{Sr}(\text{Cl}, \text{Br}, \text{I})_2\text{:Eu}^{2+}$	425	$\text{Sr}_2\text{B}_5\text{O}_9\text{Cl:Eu}^{2+}$
407	$\text{CaAl}_4\text{O}_7\text{:Ce}^{3+}$	425–430	$(\text{Lu}, \text{Gd})_2\text{SiO}_5\text{:Ce}^{3+}$
407	$\text{CaAl}_2\text{O}_4\text{:Ce}^{3+}$	429	$\text{Ba}_2\text{Li}_2\text{Si}_2\text{O}_7\text{:Sn}^{2+}$
410	$\text{Ba}_3(\text{PO}_4)_2\text{:Eu}^{2+}$	430	$\text{GdNbO}_4\text{:Bi}^{3+}$
410	$\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}\text{:Ce}^{3+}$	432	$\text{CaWO}_4$

*continued*

Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
433	CaBr <sub>2</sub> :Eu <sup>2+</sup> in SiO <sub>2</sub>	460	Sr <sub>2</sub> P <sub>2</sub> O <sub>7</sub> :Sn <sup>2+</sup>
433	CaWO <sub>4</sub> :Pb	460	ZnS:Ag,Cl
435	CaF <sub>2</sub> :Eu <sup>2+</sup>	463, 512	CaGa <sub>2</sub> S <sub>4</sub> :Ce <sup>3+</sup>
435	Ca <sub>5</sub> (VO <sub>4</sub> ) <sub>3</sub> Cl	464	La <sub>2</sub> O <sub>3</sub> :Bi <sup>3+</sup>
435	CaWO <sub>4</sub> :Pb <sup>2+</sup>	464	SrB <sub>4</sub> O <sub>7</sub> :Pb <sup>2+</sup> ,Mn <sup>2+</sup>
437	Ba <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Eu <sup>2+</sup>	464, 532	ZnS:Au,In
438, 486	CaS:Cu <sup>+</sup> ,Na <sup>+</sup>	465	Sr <sub>2</sub> P <sub>2</sub> O <sub>7</sub> :Sn <sup>2+</sup>
440	BaSrMgSi <sub>2</sub> O <sub>7</sub> :Eu <sup>2+</sup>	465	ZnS:Ag,Ni
440	Gd <sub>2</sub> SiO <sub>5</sub> :Ce <sup>3+</sup>	467	CaI <sub>2</sub> :Eu <sup>2+</sup> in SiO <sub>2</sub>
440	MgBa <sub>3</sub> Si <sub>2</sub> O <sub>8</sub> :Eu <sup>2+</sup>	467	Sr <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub> :Eu <sup>2+</sup>
440	MgSrBa <sub>2</sub> Si <sub>2</sub> O <sub>7</sub> :Eu <sup>2+</sup>	470	SrMgSi <sub>2</sub> O <sub>6</sub> :Eu
443	CaAl <sub>2</sub> O <sub>4</sub> :Eu <sup>2+</sup>	470/540	CdWO <sub>4</sub>
443	CaS:Y <sup>3+</sup>	473	MgWO <sub>4</sub>
443	ZnS:Ag <sup>+</sup> ,Cl <sup>-</sup>	475	BaAl <sub>2</sub> S <sub>4</sub> :Eu <sup>2+</sup>
444, 530	ZnS:Cu <sup>+</sup> ,Cl <sup>-</sup>	477	YF <sub>3</sub> :Mn <sup>2+</sup> ,Th <sup>4+</sup>
445	Ba <sub>5</sub> SiO <sub>4</sub> Cl <sub>6</sub> :Eu <sup>2+</sup>	477, 521	YF <sub>3</sub> :Mn <sup>2+</sup>
446	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Eu <sup>2+</sup>	479	YPO <sub>4</sub> :Mn <sup>2+</sup> ,Th <sup>4+</sup>
447	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Eu	480	Ca <sub>3</sub> MgSi <sub>2</sub> O <sub>8</sub> :Eu <sup>2+</sup>
448	CaMgSi <sub>2</sub> O <sub>6</sub> :Eu <sup>2+</sup>	480	Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>
448	CaS:Bi <sup>3+</sup> ,Na	480	Sr <sub>6</sub> P <sub>5</sub> BO <sub>20</sub> :Eu
448, 390	CaO:Cu <sup>+</sup>	480	ZnWO <sub>4</sub>
450	BaMgAl <sub>10</sub> O <sub>17</sub> :Eu <sup>2+</sup>	480, 570	YVO <sub>4</sub> :Dy <sup>3+</sup>
450	CaS:Bi <sup>3+</sup>	485	Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>
450	Mg <sub>3</sub> Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>4</sub> :Eu <sup>2+</sup>	485	YF <sub>3</sub> :Tm <sup>3+</sup> ,Yb <sup>3+</sup>
451	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F:Sn <sup>2+</sup>	486	CaS:La <sup>3+</sup>
453	Ca <sub>2</sub> B <sub>5</sub> O <sub>9</sub> Br:Eu <sup>2+</sup>	488	ZnS:Pb <sup>2+</sup> ,Cl <sup>-</sup>
453	Ca <sub>2</sub> B <sub>5</sub> O <sub>9</sub> Cl:Eu <sup>2+</sup>	490, 680	(ErCl <sub>3</sub> ) <sub>0.25</sub> (BaCl <sub>2</sub> ) <sub>0.75</sub>
454, 490	BaGa <sub>2</sub> S <sub>4</sub> :Ce <sup>3+</sup>	490–630	Y <sub>2</sub> O <sub>2</sub> S:Eu <sup>3+</sup>
454, 490	SrGa <sub>2</sub> S <sub>4</sub> :Ce <sup>3+</sup>	492	α-Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Eu <sup>2+</sup>
454—800	ZnS-CdS:Ag <sup>+</sup> ,Cl	492	BaGa <sub>2</sub> S <sub>4</sub> :Eu <sup>2+</sup>
455–504	ZnS:Cu	492	Sr <sub>5</sub> Si <sub>4</sub> O <sub>10</sub> Cl <sub>6</sub> :Eu <sup>2+</sup>
456	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Eu <sup>2+</sup>	492, 500,	
456	ZnS-CdS:Cu,I	656	ThO <sub>2</sub> :Pr <sup>3+</sup>
456, 514	BaMgAl <sub>10</sub> O <sub>17</sub> :Eu <sup>2+</sup> ,Mn <sup>2+</sup>	493	SrIn <sub>2</sub> O <sub>4</sub> :Pr <sup>3+</sup> ,Al <sup>3+</sup>
459	Sr <sub>3</sub> MgSi <sub>2</sub> O <sub>8</sub> :Eu <sup>2+</sup>	494	(Ba,Ti) <sub>2</sub> P <sub>2</sub> O <sub>7</sub> :Ti
459	ZnS:Cl <sup>-</sup>	495	BaTiP <sub>2</sub> O <sub>7</sub>
460	ZnGa <sub>2</sub> O <sub>4</sub>	496	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F:Sb <sup>3+</sup>

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Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
496	$\text{CaF}_2:\text{Ce}^{3+}, \text{Mn}^{2+}$	521	$\text{Ca}_5(\text{PO}_4)_3\text{Cl}:\text{Sb}^{3+}$
496	$\text{CaF}_2:\text{Mn}^{2+}$	521	$\text{ZnS}:\text{Cu}^+, \text{Al}^{3+}$
496	$\text{MgWO}_4$	521, 528	$\text{CaS}:\text{Ce}^{3+}$
496	$\text{SrAl}_2\text{S}_4:\text{Eu}^{2+}$	522	$\text{LiAl}_5\text{O}_8:\text{Mn}^{2+}$
496, 670	$\text{CaS}:\text{Pr}^{3+}, \text{Pb}^{2+}, \text{Cl}$	522	$\text{LiAlO}_2:\text{Mn}^{2+}$
498	$\text{KGa}_{11}\text{O}_{17}:\text{Mn}^{2+}$	523	$\text{SrAl}_2\text{O}_4:\text{Eu}^{2+}$
502	$\text{BaAl}_2\text{O}_4:\text{Eu}^{2+}$	525	$\text{CdS}:\text{In}$
502	$\text{ZnGa}_2\text{O}_4:\text{Mn}^{2+}$	525	$\text{MgAl}_2\text{O}_4:\text{Mn}^{2+}$
502, 564	$\text{SrS}:\text{Ce}^{3+}$	525	$\text{SrBaSiO}_4:\text{Eu}^{2+}$
504	$\text{BaSi}_2\text{O}_5:\text{Eu}^{2+}$	525	$\text{Zn}_2\text{SiO}_4:\text{Mn}^{2+}, \text{As}^{5+}$
504	$\text{Ca}_2\text{Ba}_3(\text{PO}_4)_3\text{Cl}:\text{Eu}^{2+}$	525	$\text{Zn}_2\text{SiO}_4:\text{Mn}^{2+}$
504	$\text{MgGa}_2\text{O}_4:\text{Mn}^{2+}$	527	$\text{ZnS}-\text{CdS}:\text{Cu}, \text{Br}$
504	$\text{ZnO}:\text{Zn}$	528	$\text{CaSO}_4:\text{Ce}^{3+}, \text{Mn}^{2+}$
505	$\text{SrGa}_{12}\text{O}_{19}:\text{Mn}^{2+}$	528	$\text{Zn}_2\text{SiO}_4:\text{Mn}^{2+}, \text{As}^{5+}$
506	$\text{ZnO}:\text{S}$	528	$\text{ZnS}-\text{CdS}:\text{Cu}, \text{Br}$
508	$\alpha\text{-Ca}_3(\text{PO}_4)_2:\text{Sn}^{2+}$	528, 608	$\text{Zn}_2\text{SiO}_4:\text{Mn}^{2+}, \text{P}$
508	$\text{Ba}_2\text{Li}_2\text{Si}_2\text{O}_7:\text{Eu}^{2+}$	528, 649	$(\text{Zn}+\text{Be})_2\text{SiO}_4:\text{Mn}^{2+}$
508	$\text{Ba}_2\text{SiO}_4:\text{Eu}^{2+}$	529	$\text{CaF}_2:\text{U}$
509, 575	$\text{Sr}_5(\text{PO}_4)_3\text{F}:\text{Sb}^{3+}, \text{Mn}^{2+}$	530	$\text{CaB}_2\text{O}_4:\text{Mn}^{2+}$
510	$\text{Sr}_5(\text{PO}_4)_3\text{F}:\text{Sb}^{3+}$	530	$\text{CaMoO}_4$
510	$\text{Gd}_2\text{O}_2\text{S}:\text{Pr}^{3+}$	530	$\text{Y}_3\text{Al}_5\text{O}_{12}:\text{Ce}^{3+}$
510	$\text{Gd}_2\text{O}_2\text{S}:\text{Pr}, \text{Ce}, \text{F}$	532	$\text{SrS}:\text{Cu}^+, \text{Na}$
510	$\text{Sr}_5(\text{PO}_4)_3\text{F}:\text{Sb}^{3+}$	534	$\text{Ba}_2\text{Li}_2\text{Si}_2\text{O}_7:\text{Sn}^{2+}, \text{Mn}^{2+}$
512	$\text{Ba}_2\text{MgSi}_2\text{O}_7:\text{Eu}^{2+}$	535	$\text{Ca}_2\text{B}_2\text{O}_5:\text{Mn}^{2+}$
512	$\text{Sr}_x\text{Ba}_y\text{Cl}_z\text{Al}_2\text{O}_{4-z/2}:\text{Mn}^{2+}, \text{Ce}^{3+}$	537	$\text{Sr}_5(\text{PO}_4)_3\text{Cl}:\text{Sb}^{3+}$
513	$\text{Y}_2\text{O}_2\text{S}:\text{Pr}^{3+}$	537	$\text{SrGa}_2\text{S}_4:\text{Eu}^{2+}$
514	$\beta\text{-SrO}\cdot 3\text{B}_2\text{O}_3:\text{Pb}^{2+}, \text{Mn}^{2+}$	537	$\text{YAl}_3\text{B}_4\text{O}_{12}:\text{Th}^{4+}, \text{Ce}^{3+}, \text{Mn}^{2+}$
514	$\text{Ca}_{0.5}\text{Ba}_{0.5}\text{Al}_{12}\text{O}_{19}:\text{Ce}^{3+}, \text{Mn}^{2+}$	537	$\text{Zn}_2\text{GeO}_4:\text{Mn}^{2+}$
514	$\text{Ca}_3\text{SiO}_4\text{Cl}_2:\text{Eu}^{2+}$	539	$\text{CaO}:\text{Sb}^{3+}$
514	$\text{Ca}_3\text{WO}_6:\text{U}$	539	$\text{CaP}_2\text{O}_6:\text{Mn}^{2+}$
514	$\text{ZnAl}_2\text{O}_4:\text{Mn}^{2+}$	539	$\text{CaS}:\text{Sn}^{2+}$
514	$\text{ZnS}:\text{Cu}, \text{Sn}$	539	$\text{CaS}:\text{Sn}^{2+}, \text{F}$
517	$\text{CaLaB}_3\text{O}_7:\text{Ce}^{3+}, \text{Mn}^{2+}$	540	$\text{MgBa}_2(\text{PO}_4)_2:\text{U}$
519	$\text{CdS}:\text{In}$	540	$\text{ZnS}:\text{Pb}, \text{Cu}$
519	$\text{SrAl}_{12}\text{O}_{19}:\text{Ce}^{3+}, \text{Mn}^{2+}$	540	$\text{ZnS}-\text{CdS}(75-25)$
520	$\text{MgBa}_2(\text{PO}_4)_2:\text{Sn}^{2+}$	542	$\text{Ca}_2\text{MgSi}_2\text{O}_7:\text{Eu}^{2+}$
520	$\text{SrAl}_{12}\text{O}_{19}:\text{Eu}^{2+}, \text{Mn}^{2+}$	542	$\text{LaSiO}_3\text{Cl}:\text{Ce}^{3+}, \text{Tb}^{3+}$

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Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
542	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Ce <sup>3+</sup> , Tb <sup>3+</sup>	550, 665	YF <sub>3</sub> :Er <sup>3+</sup> , Yb <sup>3+</sup>
542	ZnB <sub>2</sub> O <sub>4</sub> :Mn <sup>2+</sup>	550, 670	BaY <sub>2</sub> F <sub>8</sub> :Er <sup>3+</sup> , Yb <sup>3+</sup>
542, 550	Y <sub>2</sub> O <sub>3</sub> :Tb <sup>3+</sup>	551, 636	ZnS:Eu <sup>2+</sup>
542, 689	Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub> :Eu <sup>2+</sup> , Mn <sup>2+</sup>	551	Ba <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:U
542–549	CaS:Tb <sup>3+</sup>	551	Sr <sub>3</sub> WO <sub>6</sub> :U
542–549	Gd <sub>2</sub> O <sub>2</sub> S:Tb <sup>3+</sup>	551	ZnS:Eu <sup>2+</sup>
542–549	Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3+</sup>	556	Sr <sub>2</sub> SiO <sub>4</sub> :Eu <sup>2+</sup>
543	CaAl <sub>2</sub> O <sub>4</sub> :Tb <sup>3+</sup>	556–608	CaS:Sm <sup>3+</sup>
543	MgCeAl <sub>11</sub> O <sub>19</sub> :Tb <sup>3+</sup>	559	CaGa <sub>2</sub> S <sub>4</sub> :Eu <sup>2+</sup>
543	ThO <sub>2</sub> :Tb <sup>3+</sup>	559	MgF <sub>2</sub> :Mn <sup>2+</sup>
543	Y <sub>2</sub> O <sub>3</sub> :Ce <sup>3+</sup> , Tb <sup>3+</sup>	560	CsI:Tl
543	Y <sub>2</sub> O <sub>3</sub> :Tb <sup>3+</sup> in SiO <sub>2</sub>	560	Zn <sub>0.6</sub> Cd <sub>0.4</sub> S:Ag
543	YAlO <sub>3</sub> :Tb <sup>3+</sup>	562	Y <sub>2</sub> O <sub>3</sub> :Er <sup>3+</sup>
543	ZnS:Ag, Cu, Cl	563	Ba <sub>3</sub> WO <sub>6</sub> :U
544	(Y, Gd)BO <sub>3</sub> :Tb <sup>3+</sup>	564	CaAl <sub>4</sub> O <sub>7</sub> :Pb <sup>2+</sup> , Mn <sup>2+</sup>
544	Ca <sub>2</sub> La <sub>2</sub> BO <sub>6.5</sub> :Pb <sup>2+</sup>	564–644	LaAlO <sub>3</sub> :Sm <sup>3+</sup>
544	CaAl <sub>2</sub> O <sub>4</sub> :Mn <sup>2+</sup>	566	SrSO <sub>4</sub> :Eu <sup>2+</sup> , Mn <sup>2+</sup>
544	La <sub>2</sub> O <sub>2</sub> S:Tb <sup>3+</sup>	566–620	CaO:Sm <sup>3+</sup>
544	SrS:Mn <sup>2+</sup>	571	CaSiO <sub>3</sub> :Pb <sup>2+</sup> , Mn <sup>2+</sup>
544	Y <sub>2</sub> O <sub>2</sub> S:Tb <sup>3+</sup>	571	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F:Mn <sup>2+</sup>
544	Y <sub>2</sub> O <sub>3</sub> :Ho <sup>3+</sup>	573	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> F:Mn <sup>2+</sup>
544	Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub> :Tb <sup>3+</sup>	574	Li <sub>2</sub> CaP <sub>2</sub> O <sub>7</sub> :Ce <sup>3+</sup> , Mn <sup>2+</sup>
544–549	CaO:Tb <sup>3+</sup>	574	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Mn <sup>2+</sup>
545	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Ce <sup>3+</sup> , Mn <sup>2+</sup>	575	Mg <sub>3</sub> SiO <sub>3</sub> F <sub>4</sub> :Ti <sup>4+</sup>
545	YPO <sub>4</sub> :Ce <sup>3+</sup> , Tb <sup>3+</sup>	577–630	YOBBr:Eu <sup>3+</sup>
546	(Ce, Tb)MgAl <sub>11</sub> O <sub>19</sub> :Ce: Tb	577–670	LiInO <sub>2</sub> :Sm <sup>3+</sup>
546	(La, Ce, Tb)PO <sub>4</sub> :Ce: Tb	577–695	LaAsO <sub>4</sub> :Eu <sup>3+</sup>
546	CaF <sub>2</sub> :Ce <sup>3+</sup> , Tb <sup>3+</sup>	579	ZnS:P
546	CaS:Sb <sup>3+</sup>	579	ZnS:P <sup>3-</sup> , Cl <sup>-</sup>
546	CaS:Sb <sup>3+</sup> , Na	580	Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub> :Eu <sup>3+</sup>
546	CaS:Tb <sup>3+</sup> , Cl	582	ZnS:Mn <sup>2+</sup>
546	La <sub>2</sub> O <sub>3</sub> :Pb <sup>2+</sup>	582	ZnS-CdS:Ag, Br, Ni
550	(Zn, Cd)S:Cu	584	ZnS:Mn, Cu
550	CsI:Tl <sup>+</sup>	585	KMgF <sub>3</sub> :Mn <sup>2+</sup>
550	Na <sub>3</sub> Ce(PO <sub>4</sub> ) <sub>2</sub> :Tb <sup>3+</sup>	585	MgCaP <sub>2</sub> O <sub>7</sub> :Mn <sup>2+</sup>
550	NaYF <sub>4</sub> :Er <sup>3+</sup> , Yb <sup>3+</sup>	585	ZnF <sub>2</sub> :Mn <sup>2+</sup>
550	Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub> :Ce <sup>3+</sup>	585, 689	CaMgSi <sub>2</sub> O <sub>6</sub> :Eu <sup>2+</sup> , Mn <sup>2+</sup>

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Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
586	LaAlB <sub>2</sub> O <sub>6</sub> :Eu <sup>3+</sup>	608	CaS:Pb <sup>2+</sup> , Mn <sup>2+</sup>
586, 591,		608	SrGa <sub>2</sub> S <sub>4</sub> :Pb <sup>2+</sup>
683, 695	LaPO <sub>4</sub> :Eu <sup>3+</sup>	608	SrSO <sub>4</sub> :Bi
586–699	LaVO <sub>4</sub> :Eu <sup>3+</sup>	608	YBO <sub>3</sub> :Eu <sup>3+</sup>
588	CaS:Mn <sup>2+</sup>	609	CaYBO <sub>4</sub> :Eu <sup>3+</sup>
588	MgS:Eu <sup>2+</sup>	610	(Y,Gd) <sub>2</sub> O <sub>3</sub> :Eu <sup>3+</sup>
588, 660	MgB <sub>2</sub> O <sub>4</sub> :Mn <sup>2+</sup>	610	(Ca,Zn,Mg) <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Sn
588, 827	CaO:Tl <sup>+</sup>	610	CaSiO <sub>3</sub> :Mn <sup>2+</sup> , Pb
589–627	YOF:Eu <sup>3+</sup>	610	Y <sub>1.34</sub> Gd <sub>0.60</sub> O <sub>3</sub> (Eu,Pr) <sub>0.06</sub>
590	(Zn,Mg)F <sub>2</sub> :Mn <sup>2+</sup>	611	Ca <sub>5</sub> B <sub>2</sub> SiO <sub>10</sub> :Eu <sup>3+</sup>
590	Ca <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Mn <sup>2+</sup>	611	CaGa <sub>2</sub> S <sub>4</sub> :Pb <sup>2+</sup>
590	CaGa <sub>2</sub> O <sub>4</sub> :Mn <sup>2+</sup>	611	CaLaBO <sub>4</sub> :Eu <sup>3+</sup>
590	CaGa <sub>4</sub> O <sub>7</sub> :Mn <sup>2+</sup>	611	CaYB <sub>0.8</sub> O <sub>3.7</sub> :Eu <sup>3+</sup>
590	CaO:Eu <sup>3+</sup> , Na <sup>+</sup>	611	Na <sub>1.23</sub> K <sub>0.42</sub> Eu <sub>0.12</sub> TiSi <sub>4</sub> O <sub>11</sub> :Eu <sup>3+</sup>
590	KMgF <sub>3</sub> :Mn <sup>2+</sup>	611	SrY <sub>2</sub> O <sub>3</sub> :Eu <sup>3+</sup>
590	MgF <sub>2</sub> :Mn <sup>2+</sup>	611	Y <sub>2</sub> O <sub>3</sub> :Eu <sup>3+</sup>
590	Sr <sub>5</sub> (PO <sub>4</sub> ) <sub>3</sub> Cl:Eu <sup>2+</sup> , Pr <sup>3+</sup>	612	CaTiO <sub>3</sub> :Eu <sup>3+</sup>
590	Y <sub>4</sub> Al <sub>2</sub> O <sub>9</sub> :Eu <sup>3+</sup>	612	CaTiO <sub>3</sub> :Pr <sup>3+</sup>
592, 608,		612	NaYO <sub>2</sub> :Eu <sup>3+</sup>
629	ThO <sub>2</sub> :Eu <sup>3+</sup>	612	SrAl <sub>4</sub> O <sub>7</sub> :Eu <sup>3+</sup>
593	CaCl <sub>2</sub> :Eu <sup>2+</sup> , Mn <sup>2+</sup> in SiO <sub>2</sub>	612	Y <sub>2</sub> O <sub>3</sub> :Eu <sup>3+</sup> in SiO <sub>2</sub>
593, 619		614	CaMoO <sub>4</sub> :Eu <sup>3+</sup>
696	YVO <sub>4</sub> :Eu <sup>3+</sup>	614	CaSO <sub>4</sub> :Bi
593, 611,		614	LaBO <sub>3</sub> :Eu <sup>3+</sup>
629	(Y,Gd)BO <sub>3</sub> :Eu <sup>3+</sup>	614	LaOCl:Eu <sup>3+</sup>
593, 619,		614	YAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> :Eu <sup>3+</sup>
696	Y(P,V)O <sub>4</sub> :Eu <sup>3+</sup>	614	β-Sr <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> :Sn <sup>2+</sup> , Mn <sup>2+</sup> (Al)
594, 617,		614–699	LiLaO <sub>2</sub> :Eu <sup>3+</sup>
702	K <sub>2</sub> La <sub>2</sub> Ti <sub>3</sub> O <sub>10</sub> :Eu <sup>3+</sup>	615	Ba <sub>2</sub> SiO <sub>4</sub> :Ce <sup>3+</sup> , Li <sup>+</sup> , Mn <sup>2+</sup>
595, 620,		615	CaO:Eu <sup>3+</sup>
710	YPO <sub>4</sub> :Eu <sup>3+</sup>	615	SrTiO <sub>3</sub> :Pr <sup>3+</sup>
596	KMgF <sub>3</sub> :Mn <sup>2+</sup>	615	YAsO <sub>4</sub> :Eu <sup>3+</sup>
599	CaO:Mn <sup>2+</sup>	615	LiCeBa <sub>4</sub> Si <sub>4</sub> O <sub>14</sub> :Mn <sup>2+</sup>
600	ZnS–CdS (50–50)	615	LiCeSrBa <sub>3</sub> Si <sub>4</sub> O <sub>14</sub> :Mn <sup>2+</sup>
602	YAlO <sub>3</sub> :Sm <sup>3+</sup>	615–695	YAlO <sub>3</sub> :Eu <sup>3+</sup>
605	LaAlO <sub>3</sub> :Eu <sup>3+</sup>	617	CaGeO <sub>3</sub> :Mn <sup>2+</sup>
605	LiInO <sub>2</sub> :Eu <sup>3+</sup>	617	CaY <sub>2</sub> ZrO <sub>6</sub> :Eu <sup>3+</sup>

*continued*

Wavelength (nm)	Chemical formula	Wavelength (nm)	Chemical formula
617	SrTiO <sub>3</sub> :Pr <sup>3+</sup> ,Al <sup>3+</sup>	642	BaS: Au, K
618	CdS: In, Te	645	ZnO: Bi <sup>3+</sup>
620	La <sub>2</sub> W <sub>3</sub> O <sub>12</sub> : Eu <sup>3+</sup>	646	β-Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Sn <sup>2+</sup>
620	LaAl <sub>3</sub> B <sub>4</sub> O <sub>12</sub> : Eu <sup>3+</sup>	646	ZnGa <sub>2</sub> S <sub>4</sub> : Mn <sup>2+</sup>
620	MgYBO <sub>4</sub> : Eu <sup>3+</sup>	646	ZnS: Mn <sup>2+</sup> , Te <sup>2+</sup>
620	Na <sub>1.23</sub> K <sub>0.42</sub> Eu <sub>0.12</sub> TiSi <sub>5</sub> O <sub>13</sub> · xH <sub>2</sub> O: Eu <sup>3+</sup>	646	ZnSe: Cu <sup>+</sup> , Cl
620	SrS: Eu <sup>2+</sup>	649	CaS: Eu <sup>2+</sup>
620	YOCl: Eu <sup>3+</sup>	646	ZnS-ZnTe: Mn <sup>2+</sup> 98-2
620	ZnMg <sub>2</sub> (PO <sub>4</sub> ) <sub>2</sub> : Mn <sup>2+</sup>	650	ZnS: Te, Mn
621	CaYAlO <sub>4</sub> : Eu <sup>3+</sup>	658	Mg <sub>2</sub> TiO <sub>4</sub> : Mn <sup>4+</sup>
623	LiAlF <sub>4</sub> : Mn <sup>2+</sup>	658	Mg <sub>4</sub> (F)(Ge, Sn)O <sub>6</sub> : Mn <sup>2+</sup>
623	ZnS: Sn, Ag	658	Mg <sub>4</sub> (F)GeO <sub>6</sub> : Mn <sup>2+</sup>
623	ZnS: Pb, Cu	660	Mg <sub>2</sub> SiO <sub>4</sub> : Mn <sup>2+</sup>
623	ZnS: Sn <sup>2+</sup> , Li <sup>+</sup>	660	Mg <sub>8</sub> Ge <sub>2</sub> O <sub>11</sub> F <sub>2</sub> : Mn <sup>4+</sup>
625	Cd <sub>2</sub> B <sub>6</sub> O <sub>11</sub> : Mn <sup>2+</sup>	660	ZnS-CdS (25-75)
625	La <sub>2</sub> O <sub>3</sub> : Eu <sup>3+</sup>	661	SrMoO <sub>4</sub> : U
626	(Sr, Mg) <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Sn	680	α-SrO·3B <sub>2</sub> O <sub>3</sub> : Sm <sup>2+</sup>
626	LaOF: Eu <sup>3+</sup>	681	LiAl <sub>5</sub> O <sub>8</sub> : Fe <sup>3+</sup>
626	ZnO: Se	681	MgSr <sub>3</sub> Si <sub>2</sub> O <sub>8</sub> : Eu <sup>2+</sup> , Mn <sup>2+</sup>
626	ZnS: Pb <sup>2+</sup>	684-732	Sr <sub>w</sub> F <sub>x</sub> B <sub>y</sub> O <sub>z</sub> : Eu <sup>2+</sup> , Sm <sup>2+</sup>
627	Gd <sub>2</sub> O <sub>2</sub> S: Eu <sup>3+</sup>	685	SrB <sub>8</sub> O <sub>13</sub> : Sm <sup>2+</sup>
629	β-(Ca, Sr) <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Sn <sup>2+</sup> , Mn <sup>2+</sup>	688, 707,	
629	Be <sub>2</sub> SiO <sub>4</sub> : Mn <sup>2+</sup>	725	Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub> : Cr <sup>3+</sup>
630	K <sub>2</sub> SiF <sub>6</sub> : Mn <sup>4+</sup>	689	ZnS: Sn
630	Zn <sub>0.4</sub> Cd <sub>0.6</sub> S: Ag	695	Na(Mg <sub>2-x</sub> Mn <sub>x</sub> )LiSi <sub>4</sub> O <sub>10</sub> F <sub>2</sub> : Mn
633	(Zn, Mg) <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Mn <sup>2+</sup>	713	CaGa <sub>2</sub> S <sub>4</sub> : Mn <sup>2+</sup>
635	Zn <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Mn <sup>2+</sup>	730	Gd <sub>3</sub> Ga <sub>5</sub> O <sub>12</sub> : Cr, Ce
636	CaI <sub>2</sub> : Eu <sup>2+</sup> , Mn <sup>2+</sup> in SiO <sub>2</sub>	730	Gd <sub>3</sub> Ga <sub>5</sub> O <sub>12</sub> : Cr <sup>3+</sup>
639	Zn <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> : Mn <sup>2+</sup>	742	LiAlO <sub>2</sub> : Fe <sup>3+</sup>
640	CdS: Te	747	CaS: Yb <sup>2+</sup>
640	MgSiO <sub>3</sub> : Mn <sup>2+</sup>	747	CaS: Yb <sup>2+</sup> , Cl
640	MgSr <sub>5</sub> (PO <sub>4</sub> ) <sub>4</sub> : Sn <sup>2+</sup>	760	CaTi <sub>0.9</sub> Al <sub>0.1</sub> O <sub>3</sub> : Bi <sup>3+</sup>
640, 667	Y <sub>3</sub> Al <sub>5</sub> O <sub>12</sub> : Mn <sup>4+</sup>	800	CdS: Ag <sup>+</sup> , Cl <sup>-</sup>
641	ZnBa <sub>2</sub> S <sub>3</sub> : Mn <sup>2+</sup>	1540	Na <sub>1.29</sub> K <sub>0.46</sub> Er <sub>0.08</sub> TiSi <sub>4</sub> O <sub>11</sub> : Eu <sup>3+</sup>

## APPENDIX III

### Willi Lehmann: A Brief Biography

Information about Willi's early life in Germany has been kindly supplied by one of his sons, Hans, in the form of brief autobiography Willi wrote for his family in 1990. Willi was born in 1914 in Dinslaken am Niederrhein. He finished elementary school in 1928 and attended a trade school for gardeners until 1931 as preparation for taking responsibilities in the family's plant nursery business. Unavoidably, world events intruded into his pastoral life and set him on a long odyssey, which would eventually bring him into the international phosphor community. Hitler assumed power in Germany in 1933 and of course affected the course of history dramatically and disastrously. Willi had a brief flirtation with the SA but did not become a member; instead, in 1934 he joined the *Deutscher Luftsport Verband*, one of the glider club precursors to the *Luftwaffe*. Participation in the club activities naturally led to his gravitating to the air force when his time came for military service in 1936.

His boot camp was in East Prussia and he did not take well to the training which was according to him "...hot, dirty and plain stupid." He consequently volunteered to become a photographer for the air force when an opportunity arose. He completed a photography course in Tutow and in 1939–1940 was promoted to corporal (*Unteroffizier*) as the head of a small photo group at the *Luftkreissschule* in Werden, near Berlin. In the Fall of 1941, Willi was assigned to a long range reconnaissance unit on the Eastern front at Luga near Leningrad. With the war situation in flux through 1943, he found himself moving from place to place with his unit...in Cherkov (Ukraine), Kiev, Breslau (Wroclaw), Smolensk, and Minsk. After a short interlude as an engineering student, he was promoted to sergeant (*Feldwebel*) in December 1944 and immediately assigned to an active combat unit defending the home front. He was captured by American forces on February 28, 1945 and interned in Le Mans, France.

While a U.S. prisoner, Willi demonstrated some of his intrinsic versatility for in short order he became the camp's typewriter repairman. Later he moved on to become a truck mechanic in the motor pool which moved to Le Havre in December 1945. With each change of position, his circumstances in the camp improved so much so that in the summer of 1946 he made his first of five escape attempts.

On his first two escape attempts, he was recaptured in France by the French and interned first in Sedan and then near the Belgian border. On his third attempt, he was able to cross into Belgium but was captured and interned by the Belgians. He worked variously as a miner, a camp librarian and as a farmer's aid during his captivity in Belgium. He attempted again to get home in June of 1947 was caught again and confined to solitary for a period. In September of 1947, Willi managed to construct a workable bicycle out of parts from discarded bikes and was able to ride all the way to Germany and a joyful family reunion in Dinslaken.

Willi possessed a keen intellectual sense and a deep natural curiosity. From his teens and in his own words, "Work in father's nursery was pretty dull, and I started to dream about one day becoming an engineer or scientist." With the encouragement of a library clerk, he began reading mathematics books and establishing a technical background which he drew on for the rest of his life. For example, while engaged in the glider *Verband*, he became interested and did some calculations and some nascent experiments in rocket propulsion. He submitted a report on his work to the Air Ministry (*Reichluftfahrtministerium*); though the report went no further, Willi was offered a post as photographer at the rocket facilities in Peenemunde which he declined.

In the middle of his posting to the Eastern Front, Willie was granted an extended leave so that he could attend an engineering school in Germany. This proved to be a problem since he did not possess the proper credentials (*arbitur*) to matriculate in a university level program having attended a trade rather than a traditional *Gymnasium*. Through a special dispensation, he was allowed to attend the *Techschule* in Duisberg. It was here that he was first encountered physics as a discipline and it immediately piqued his interest. In order to bypass the *arbitur* requirements, Willi attempted and passed a *Begrabtemprufung* (examination for the gifted) in the summer of 1944, just in time to return to the war.

Following his return to Germany, Willi along with a wartime friend, Claus Haake, applied for admission to the Technical University of Braunschweig in October 1947. As their initiation as students, they had to help in the reconstruction of university buildings and other facilities destroyed during the hostilities. Instruction commenced at the University in march 1948. Willi recalled that his first instructor was Erich Krautz who not only taught the Applied Physics course but also nurtured him through to his candidacy in physics (*Cand. Phys.*) in 1950. Professor Krautz also succeeded in getting Willi a scholarship which covered all his school expenses and relieved the financial burden on the Lehmann family now headed by an older brother, Paul, Willi's father having passed on in 1942.

Willi and Claus Haake obtained their *Diplom. Physiker's* (equivalent to American M.S. degree) in 1952. In view of the dearth of jobs for physicists in postwar Germany, Professor Krautz directed them to apply for positions in the lamp division of Westinghouse Electric then located in Bloomfield, New Jersey. Both were offered positions, accepted, and arrived in the States on October 1953 following an extended wait for immigration documents. During the waiting period, Willi met, wooed and wed Renate Bauer. The new Mrs. Lehmann, of course, accompanied Willi to the States and their four children (Caren, George, Hans, and Mary) were all born in the United States.

On arrival at Westinghouse, Willi was given the choice of areas to investigate. He chose to study electroluminescence and electroluminescent phosphors. His contributions in this field and his other activities at Bloomfield and later at Westinghouse R&D in Pittsburgh are detailed in the Foreword. It is interesting to note that by 1956, Willi's work on electroluminescence had attracted sufficient interest that he was approached by the University at Braunschweig to explore the possibilities of submitting his work in partial fulfillment of requirements for a doctorate degree. Indeed, his thesis entitled "The Electroluminescence of Zinc Sulfide Phosphors as an Equilibrium Process" was submitted in late 1957 and accepted. He was granted the degree of Doctor of Natural Sciences (Dr.rer.Nat) shortly thereafter.

Also as noted in the Foreword, Willi retired in 1982 at the age of 68 and took up residence in North Carolina. He thought briefly about starting his own phosphor business but rejected the idea on grounds of his lack of acumen in business matters. He acted as a consultant with Rogers Corp. and with Lawrence Livermore Laboratories in the late 1980's. In the early 1980's, he developed an interest in diffraction and the limits that it imposed on resolution and was also attracted by the furor surrounding the announcement of cold fusion.

Willi passed away on January 12, 1993 from brain cancer. Mrs. Lehmann returned to Pittsburgh and currently resides there. The children and several grandchildren appear to be prospering.

William M. Yen  
Athens, Georgia

Henry F. Ivey  
Coconut Grove, Florida