Optical Orientation of Lutetium Oxyorthosilicate

Lee Brogan

Senior Honors Project Advisor:
Dr. George Schweitzer, Chemistry

5-1-2006

Abstract

The crystal structure of Lutetium Oxyorthosilicate (LSO), a scintillating gamma ray receptor for positron emission tomography, was researched. This crystal structure was to be associated with the optical properties of the crystal in such a way that boules of the substance might be reliably oriented for cutting using visible light rather than x-rays. This will lead to a substantial decrease in the cost of LSO pixel production, as the equipment for optical light orientation is much less expensive than that for x-ray orientation. An attempt was made to analyze the crystals by orienting them using cleavage planes, but this failed due to a lack of regular cleavage in LSO. Alternatively, an x-ray oriented boule segment was to be analyzed, but as the boule was too valuable to cut apart, this procedure was not viable either. The project currently awaits the revitalization of the department's x-ray machine so that an expendable crystal fragment might be x-ray oriented. The fragment will then be analyzed using index oils to determine the relationship of the optical indicatrix figure to the crystal axes.

Introduction

Positron Emission Tomography (PET) is a powerful analytical technique used to identify concentrations of positron-emitting species in one temporal and three spatial dimensions. A target molecule is labeled with a radioactive isotope of one of its constituent atoms. The most commonly used atoms are ^{11}C, ^{13}N, and ^{18}F [1], though any isotope capable of positron emission and possessing a reasonable half-life may be used. The isotope's half life must be long enough that it is possible to produce and introduce the labeled species into the subject before it decays into immeasurable quantities and short enough that it will emit measurable amounts of radiation in a relatively short period of time. Carbon, nitrogen, and fluorine are common enough in biologically active molecules to make the labeling of a large variety of molecules with these three species useful.

The metabolic information derived from PET scanning is most often combined with data from x-ray computed tomography (CT) as a source of anatomic information. CT and PET may be run simultaneously, since the two forms of radiation measured will not interfere with one another. The two techniques together greatly heighten the utility of each, as CT scans provide a reference upon which the analyte concentration map from PET may be imposed [1,2].

The most well-known application of PET is the identification of cancerous tissue. This can be achieved using 2-fluoro-2-deoxy-D-glucose (FDG) which has been labeled with the radioactive fluorine-18 atom. The glucose derivative is introduced into the circulatory system of the patient. FDG is phosphorylated in a manner similar to glucose, but is not subsequently broken down further. The labeled fluorine therefore collects in the tissue by which the glucose derivative is absorbed. The map of this concentration thus corresponds to a map of the rate of energy consumption in the body, since those areas of the body which consume more energy will

naturally break down the most glucose. Many malignant tumors display increased glucose use, and may thus be detected as areas of abnormal glucose consumption. When correlated with the CT scan of the subject, the location of these abnormal areas on the patient's body can be determined [1,3,4].

The presence of a labeled species is detectable by the PET instrumentation when the radioactive atom releases a positron. This positron travels until it encounters an electron. The mean travel distance depends upon the emitting species, but is typically on the order of a millimeter (^{18}F has a mean travel distance of 0.6 mm, while ^{13}N has a mean travel distance of 1.5 mm). The two particles annihilate each other upon contact, producing a pair of 511 keV photons traveling in opposite directions. These gamma rays may be collected by scintillating crystals capable of emitting photons of lower energy light in response to such stimuli, and two photons collected coincidently yield a "Line of Response" along which the decay event occurred [1].

A gamma ray incident upon a scintillating receptor is initially converted into a collection of electron-hole pairs. The efficiency of this conversion is determined by the vibrational frequencies of the receptor's crystalline lattice – a higher frequency will result in a less efficient conversion. The energy in these electron-hole pairs is transferred through the crystal until it reaches a luminescent ion doped into the receptor. This dopant then releases the energy as another photon, typically in the visible wavelengths, which can be easily detected by a photodiode and relayed as an electronic signal to a computer [5].

A number of features are desirable in these scintillating receptor crystals. First, higher density crystals are more likely to intercept the high frequency gamma rays. Secondly, the efficiency of the crystal's scintillation is important – if the crystal does not produce an

appreciable scintillation, it is useless. Finally, the relaxation time between the interception of the gamma ray and the scintillation must be as small as possible so that the coincidence of photons can be reliably determined [5,6].

Lutetium Oxyorthosilicate doped with Ce^{+3} ions ($Lu_2SiO_5:Ce^{+3}$, or LSO) is widely agreed to be the best scintillating receptor yet discovered for 511 keV photons. LSO has a high density of 7.4 g/cc, transmits incident energy with a 7.5% efficiency, and a relaxation time of 40 to 43 ns. Additionally, the crystal's structure is tough enough that it may be cut into the necessary pixel shapes with relative ease, and as the structure is not hygroscopic, transportation and storage of the pixels is simple. LSO outputs light at a peak wavelength of 420 nm, which is easily detected by photodiodes. The main disadvantage to LSO is the cost of production [5,6]. New methods of manufacture are constantly being sought to minimize the cost.

LSO crystals must be polished after cutting into pixels, a process which is both laborious and time consuming. It has recently been found that pixels may be polished very simply by etching, but only if they are cut with a specific orientation relative to the crystal's crystallographic axes. The normal method of orienting crystals using x-ray light, however, is extremely expensive in an industrial setting, as it is necessary to integrate the x-ray machine into the automated cutting apparatus. If a method can be found to orient these crystals using optical light rather than x-ray radiation, a much less expensive optical device may be integrated, greatly decreasing the cost of each individual pixel.

Theory

Monoclinic crystals are crystals with unit cells possessed of three axes of unequal length, two of which are perpendicular to a third axes but are not at right angles to one another.

Lutetium oxyorthosilicate displays a monoclinic crystalline structure. The dimensions of the unit cell of LSO are illustrated below in Fig. 1.

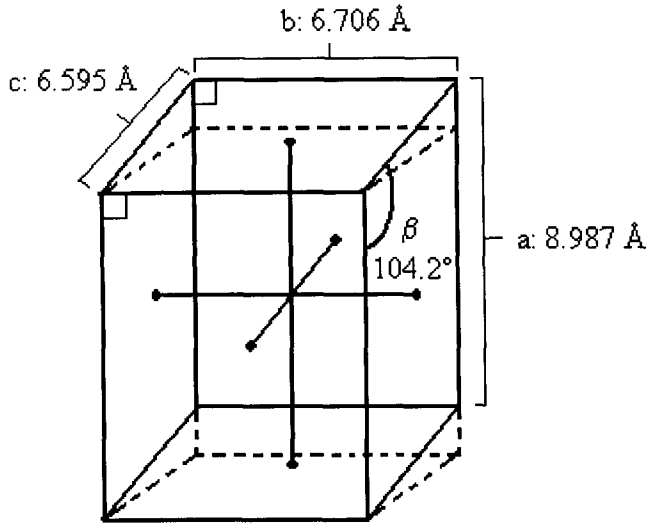

Figure 1 displays the dimensions of the unit cell of LSO. The dotted lines illustrate a rectangular prism against which may be contrasted the crystal's monoclinic nature. Information displayed comes from reference 7.

LSO is made up of pyramidal orthosilicate groups, oxygen, and both 6 and 7 coordinate lutetium atoms. The smallest unit of LSO consists of one 6 coordinate and one 7 coordinate Lu^{+3} atom, one oxygen bound to four lutetium atoms, and one orthosilicate group. The unit square of LSO is made of four of these units. The structure of this crystal is illustrated in Fig. 2 below.

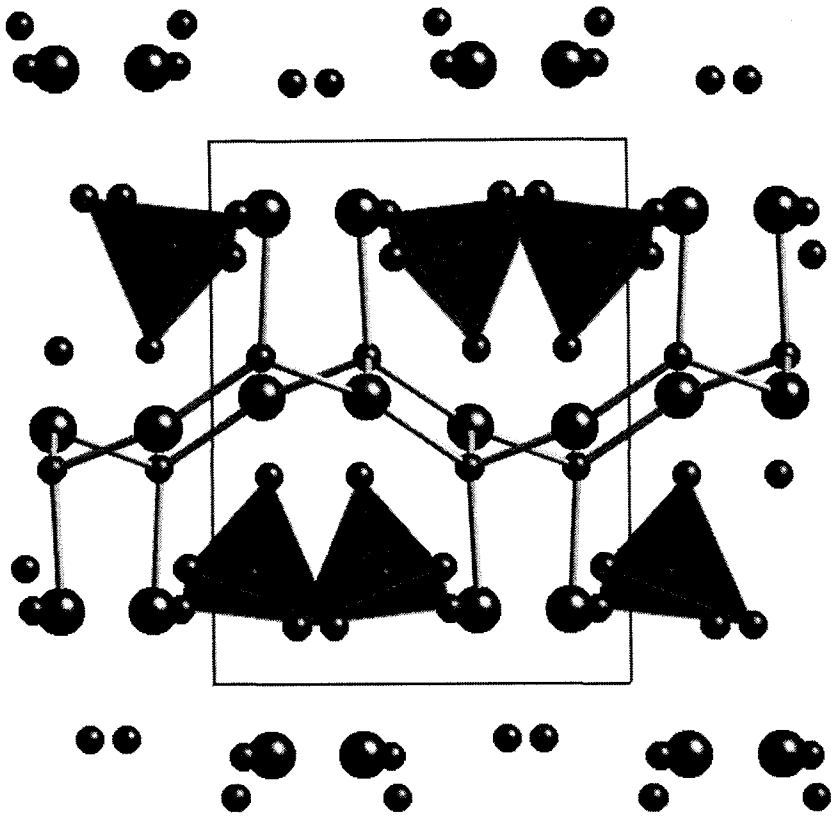

Figure 2 displays the crystalline structure of LSO viewed along the z axis: direction c in Fig. 1. The silicate groups are pyramidal structures around a central four-coordinate silicon atom. The bonds between silicate and lutetium are omitted here to enhance the clarity of the image. The box represents the unit cell of the crystal. The seven-coordinate lutetium atoms here form the horizontal line in the center of the unit cell. This image was produced with CrystalMaker 6.2.2 using data from reference 7.

Birefringence is a phenomenon observed when light which is polarized along one plane moves through a crystal at a different speed than light polarized along another plane. The difference between these two speeds equals the birefringence of the crystal. Zero birefringence occurs when the speed of light does not depend upon its polarization, as is the case in liquids and gases. Like all monoclinic crystals, LSO is optically biaxial. This means that there are two directions relative to its crystal structure, called the optical axes, along which light may pass through the crystal with zero birefringence. At all other directions, the light travels as two rays exhibiting mutually perpendicular vibrations and different speeds. In such crystals the vibration

direction of the fastest ray, called X, and that of the slowest ray, termed Z, are at right angles to each other. A third ray, Y, is perpendicular to the plane formed by X and Z, and has an index of refraction between those of the other two.

The optical properties of crystals may be visualized using a diagram known as the optical indicatrix. A general optical indicatrix for a biaxial crystal is shown in Fig. 3, below. The distance between the center of the figure and the surface of the ellipse indicates the speed of the ray, with the longer distance indicative of the lower speed. The circular cross-sections of the indicatrix are perpendicular to the optical axes and intersect along Y, indicating that the speed of light in each of these directions is always constant and equal to that of the ray of middle velocity.

In monoclinic crystals, one axis of the indicatrix always corresponds with the b axis of the crystal. Thus, a crystal oriented along the b axis will always exhibit an index of refraction equal to X, Y, or Z. The identity of this ray may be determined if the maximum and minimum indexes of refraction of the crystal are known. If the index of refraction along the b axis is equal to the maximum, this is the Z ray, if equal to the minimum, this is the X ray, and if between the two, this is the Y ray.

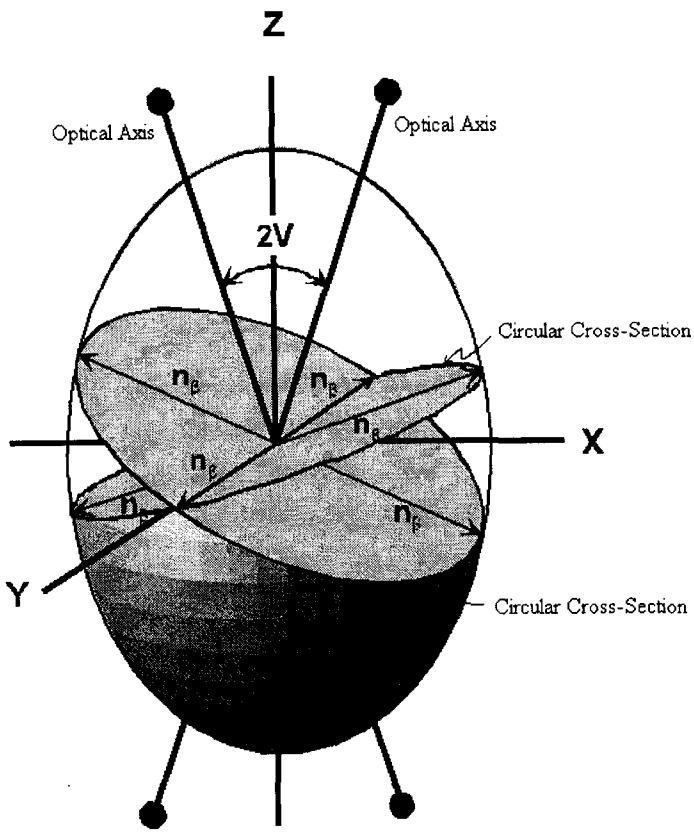

Figure 3 displays the optical indicatrix of a biaxial crystal. This figure was obtained from reference 8.

The directions of the two unknown rays may be determined through observation of the two optical axes of the crystal. The angle of each optical axis to the b axis may be measured through the observation of the point of total extinction when the mineral is viewed in convergent polarized light. Once the orientations of the two optical axes are found relative to the b axis and each other (through the measurement of 2V in Fig. 3), the optical indicatrix of the mineral will be completely known and can be related to the crystallographic axes.

Index Determination

The determination of a crystal's indexes of refraction may be carried out through the use of index oils. These are liquids of a known index of refraction in which a sample of the crystal to be analyzed may be immersed on a microscope slide. The slide is then observed with plane-

polarized light using a petrographic microscope. A crystal immersed in an oil of exactly the same index of refraction will only be discernable due to color differences between it and the index liquid, as the edge of the fragment will be invisible.

A phenomenon known as the Breke line may be used to hone in upon the index of refraction of a crystal. As the microscope slide bearing the crystal and oil is thrown out of focus, a narrow, bright line of refracted light is formed around the perimeter of the crystal. As the distance between the stage and the lens is increased, this line of light will move towards the medium with the higher refractive index. Thus, if the line moves into the crystal as the stage is lowered, the crystal has a higher index than the surrounding liquid, and a liquid of higher refractive index must be employed as a determinant [9].

Crystal Orientation

The simplest method of crystal orientation is to rely upon the cleavage of the crystal. A number of crystals will break smoothly along one or two planes with great regularity, and thus crushed fragments of the crystal will tend to lie upon those planes when placed upon a microscope slide. If a crystal displays this sort of preferred cleavage, one or two indexes of refraction will be favored, and may be measured using index oils. An analysis of the crystalline structure may then be carried out to determine the weak planes of the crystal and thus the likely fracture points, identifying the crystal orientation which corresponds to each index of refraction.

Not all crystals possess reliable planes of cleavage, and so they must be oriented by other means. Single crystal x-ray crystallography provides the most accurate method. Since the distances between atoms in a crystal are on the order of the wavelengths of an x-ray and since crystals are by definition regular structures, the diffraction pattern of x-ray light as it passes through or is bounced off of a crystal will show a certain order. This is caused by the

constructive and destructive interference of x-rays with one another as they are bounced off of different layers of the crystal's repeated structure. The actual pattern obtained depends upon the angle through which the light passes through the crystal. The crystal may be rotated until it is positioned in the desired orientation as indicated by analysis of this pattern.

Procedure and Results

Determination of Indexes of Refraction

The indexes of refraction of the crystal were studied using index oils under a petrographic microscope in plane-polarized light. The 2V of the crystal was estimated at close to 30°, indicating that not all of the optical axes will correspond with crystallographic axes. The n_1 index was found to be 1.783, and the n_3 to be 1.80. The n_2 index will lie between these two indexes and may be determined, if needed, once an oriented crystal fragment is obtained. Figure 4, below, displays a typical pair of index oils alongside a view of crystal fragments through a petrographic microscope.

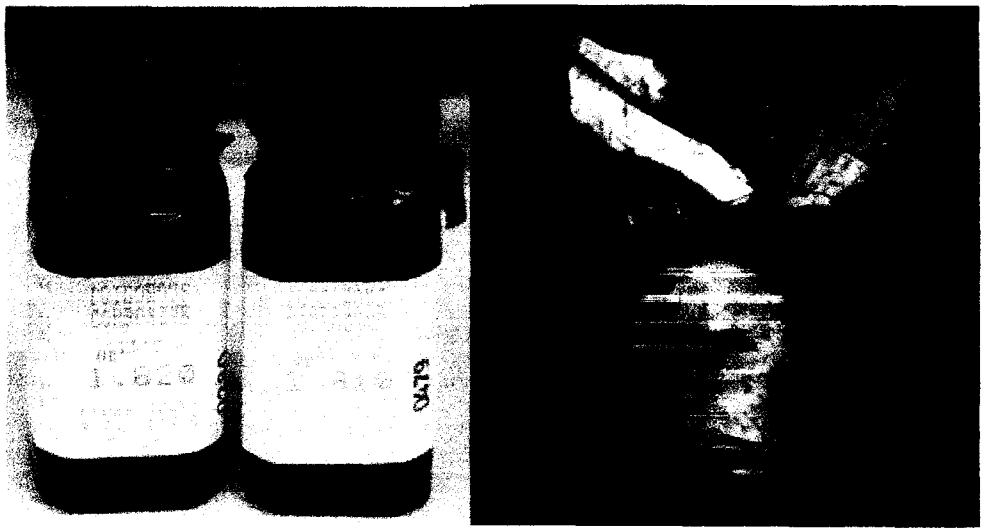

Figure 4 displays a pair of index oils used to determine the crystal's refractive indexes to the left. The right shows a view of LSO crystals seen immersed in index oil through a petrographic microscope. Interference causes the rainbow effect.

Orientation

Since relying upon the regular cleavage of a crystal is the easiest, swiftest, and least expensive method of orientation, the previously researched structure of LSO was first analyzed for potential cleavage lines. To this end, the structure was input into the program CrystalMaker 6.2.2 and the resulting computer model was examined. The most promising line of cleavage was found to lie on the yz plane, as is shown in Fig. 5.

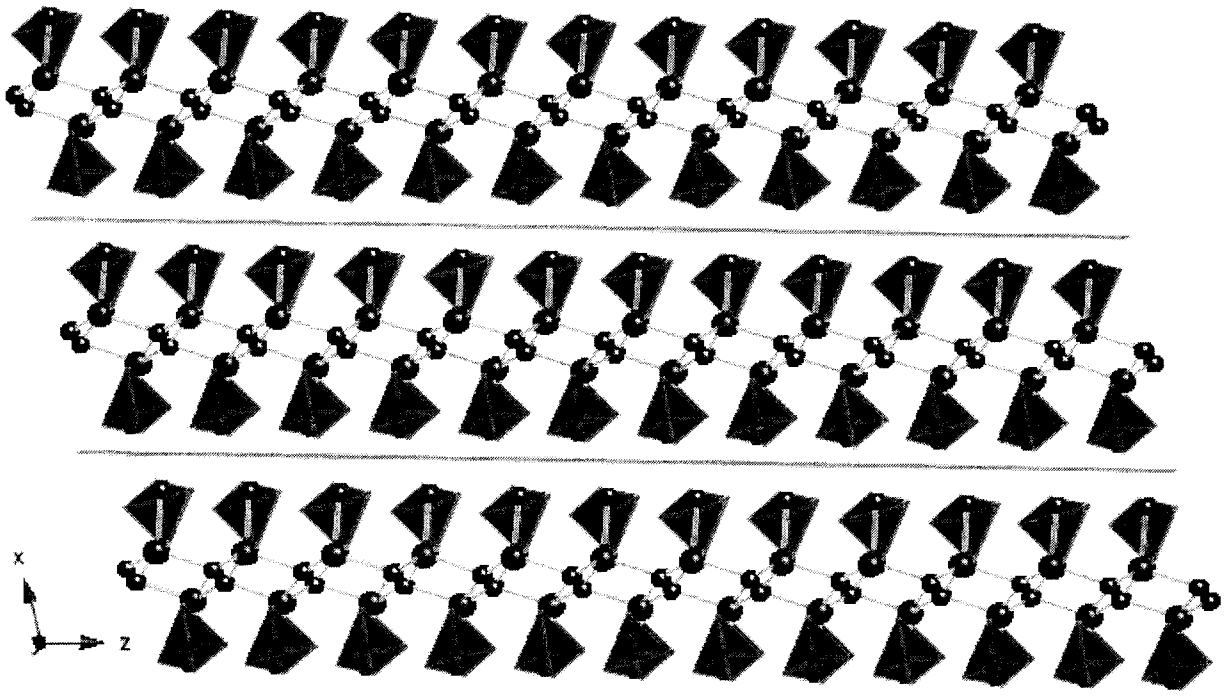

Figure 5 displays the potential xy cleavage plane, situated along bonds separating the pyramidal orthosilicate groups from lutetium.

Once the probable plane of fracture was determined, a sample of LSO crystal was obtained from among the discards of an etching experiment. The sample was crushed to a powder of around 50 microns and analyzed under plane-polarized light using a petrographic microscope.

Unfortunately, the sample displayed irregular cleavage, and so the examination did not yield any usable results.

Since cleavage is not a viable method for orienting the LSO crystal fragments, an oriented boule section was obtained. A small piece was chipped from it and analysis was undertaken. However, a clean edge could not be achieved, due again to the lack of a predictable plane of fracture. Since the boule segment was deemed too valuable to cut, another source of oriented crystals was sought.

It was decided to orient a small fragment of the crystal drawn from the same pool of discards as the crushed sample. The crystal fragment would be oriented along the b axis. The sample would then be embedded in a resin and cut along both the b axis and the perpendicular a axis, producing thin slides which will be oriented for analysis under the petrographic microscope. This final orientation, however, has not been performed, as the x-ray machine to be employed has only recently been repaired and is still undergoing rigorous calibration.

Conclusions and Future Research:

The relationship between the optical indicatrix and crystal structure of LSO may be determined through the use of two crystal samples of different and known orientation, one of which is oriented along the b crystalographic axis. These samples shall be analyzed using index oils with a petrographic microscope. However, in order to obtain these oriented samples, a single-crystal x-ray machine must be employed. As the available x-ray instrument has been a victim of chronic malfunction, this key element of the research has not yet been completed.

References:

[1] van den Hoff, J. "Principles of quantitative positron emission tomography." *Amino Acids*. 2005 Dec;29(4):341-53. Epub 2005 Jul 12.

[2] Chen YK et al., "Clinical usefulness of fused PET/CT compared with PET alone or CT alone in nasopharyngeal carcinoma patients." *Anticancer Res.* 2006 Mar-Apr; 26(2B):1471-7.

[3] Delbeke, Dominique et. al., "Procedure Guideline for Tumor Imaging with 18F-FDG PET/CT 1.0." *Journal of Nuclear Medicine* 2006, Vol. 47 No. 5, 885-895.

[4] Gomzina, N. A., D. A. Vasil'ev and R. N. Krasikova. "Optimization of Automated Synthesis of 2-[18F]Fluoro-2-deoxy-D-glucose Involving Base Hydrolysis." *Radiochemistry* July 2002 Volume 44, Number 4, 403-409.

[5] Blasse, G. "Luminescent Materials: Is There Still News?" *J. of Alloys and Compounds.* 1995, 225, 529-33.

[6] Eriksson, L.; et al. "Experience with scintillators for PET: Towards the fifth generation of PET scanners." *Nuc. Instr. & Meth. A.* **2004**, *525(1-2),* 242-248.

[7] Müller-Bunz and Thomas Schleid. *Über die Oxidsilicate $M_2O[SiO_4]$ der schweren Lanthanoide (M = Dy-Lu) im A-Typ.* Z. anorg. allg. Chem. 1998. 625, 613-618.

[8] Finn, Greg. "Biaxial Minerals Optics." 2005. Accessed Dec. 14, 2005. <http://www.brocku.ca/earthsciences/people/gfinn/optical/biaxindc.htm>

[9] Klein, Cornelis and Cornelius S. Hurlbut, Jr. *Manual of Mineralogy.* New York: John Wiley & Sons, Inc. 1999.