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FURTHER MEASUREMENTS OF THE SCINTILLATION PROPERTIES OF LEAD CARBONATE*

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ABSTRACT

Additional measurements are presented on the scintillation properties of lead carbonate ($PbCO_3$), a recently discovered, heavy inorganic scintillator. The light output of the natural crystal cerussite was measured during ^{60}Co irradiation at 23°C. After an exposure greater than 2.5 x 10^6 rad the light output increased by 25% and no visible crystal coloring occurred, thus $PbCO_3$ appears to be useful in high radiation fields. The emission spectrum was adequately described by a sum of four gaussian peaks whose position and width did not change during the irradiation. The scintillation light output is temperature dependent, increasing with temperature from 680 photons/MeV at +30°C to 3200 photons/MeV at –40°C to 11,900 photons/MeV at –120°C. The scintillation decay lifetime was measured with the delayed coincidence method between +30°C and –140°C and fit to the sum of four exponentials. At 30°C the four components are 20% at 3.9 ns, 44% at 24 ns, 26% at 186 ns, and 11% at 1.40 μs. At –40°C the four components are 24% at 37 ns, 45% at 107 ns, 18% at 359 ns, and 12% at 1.07 μs. At –120°C the four components are 0.3% at 1.8 ns, 3.5% at 3.8 ns, 40% at 539 ns, and 56% at 2.71 ns. From 30°C to –140°C the initial intensity remains constant at about 45 photons/ns/MeV. This indicates that with decreasing temperature, the energy resolution of $PbCO_3$ improves, the deadtime increases, and the timing resolution remains constant. The timing spectrum from a synthetic crystal at 25°C is fit by three components: 22% at 2.0 ns, 69% at 15 ns, and 9% at 92 ns, suggesting that some of the slower components seen in the natural crystal are due to impurities.

1. INTRODUCTION

Although many scintillators have been developed for gamma ray detection, no single scintillator has the combined stopping power of BGO, the luminosity of NaI(Tl), and the speed of BaF_2. The recently discovered scintillator lead carbonate ($PbCO_3$) combines fast decay time, a stopping power similar to that of BGO, but a low light output [1]. These properties make lead carbonate a promising candidate for a high-density high-rate gamma-ray radiation detector. The original work has been extended by measuring the scintillation properties of $PbCO_3$ as a function of radiation dose, temperature, and chemical purity.

1.1 Previous Measurements on $PbCO_3$

Although scintillation in cerussite, a naturally occurring mineral form of lead carbonate, was first observed in 1948 [2], its scintillation properties were not quantified until recently [1,3]. The material properties of $PbCO_3$ are attractive for use as a gamma-ray radiation detector, as its density is 6.6 g/cm^3, it has an attenuation length of 1.1 cm for 511 keV photons, and it is not hygroscopic. It is colorless, transmits light down to approximately 270 nm, and is birefringent with indices of refraction of 1.80 and 2.08 [4]. This birefringence is an asset, as $PbCO_3$ scintillation crystals can be oriented such that the photomultiplier tube is attached to the low index face, minimizing Fresnel reflection losses and maximizing light transmission into the photomultiplier tube. The higher index of refraction of the other faces increases the total internal reflection, making the crystal a more efficient light pipe.

The emission spectrum peak is at 475 nm, and the emission drops to less than 10% of its peak value at 370 nm and 580 nm. The fluorescence decay lifetime at +23° C, measured with the delayed coincidence method [5], is described by a sum of three exponentials; 24% of the light is emitted with a 5.6 ns time constant, 48% with a 27 ns time constant, and 28% with a 155 ns time constant. Optical quality synthetic crystals of pure lead carbonate have not been available until recently. When a 3 mm cube of a cerussite (a naturally occurring mineral form of $PbCO_3$) was excited with 511 keV photons a photopeak with a 42% full width at half maximum was observed at approximately 9% the light output of a BGO crystal with similar geometry.

2. RADIATION HARDNESS

It is desirable that a scintillator not deteriorate when exposed to high radiation doses. The gamma irradiation facility at Brookhaven National Laboratory [6] was used to determine the effect of radiation on the scintillation

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properties of $PbCO_3$. This facility uses ^{60}Co gamma rays to both induce radiation damage and excite luminescence in scintillators, and has the capability of measuring continuously the total light output and the emission spectrum during irradiation.

A natural crystal of cerussite from Tsumeb, South Africa measuring 8 mm x 8 mm x 4 mm was irradiated at the BNL facility with ^{60}Co gamma rays at a rate of 2.5 x 10^4 rad per hour for a period of 120 hours. Although $PbCO_3$ is optically anisotropic and orientation dependent effects might be present, no attempt was made to orient the crystal or search for anisotropic emission. However the crystal remained in the same position and orientation throughout the series of measurements.

2.1 Light Output vs. Radiation Dose

Both the total light output and emission spectra were measured during irradiation with a scanning monochromator equipped with a cooled, broad spectral response photomultiplier tube. One data point per second was acquired and acquisition of a new spectrum was begun every half hour. These spectra were not corrected for the wavelength dependence of the photomultiplier tube or monochromator. Figure 1 shows the emission spectrum area after background subtraction as a function of radiation dose. The output increases roughly linearly with radiation dose at a rate of 9% per Mrad of ^{60}Co irradiation. Quantitative measurement of the radiation damage ended at a total dose of 3 Mrad, but the sample was exposed to a total of 10 Mrad without any visible coloration. While it is unusual for luminescence to increase with radiation dose, this effect has been observed before in BC-408 and BC-412 plastic scintillator [7]. Four examples of luminescence mechanisms that could lead to increasing light output with radiation dose are: 1) the unirradiated crystals contain absorption bands that are removed by radiation, 2) the luminescence is due to a lattice defect produced by radiation, 3) the luminescence is due to a charge transfer process that is in competition with recombination at traps, and radiation reduces the recombination probability at the traps, 4) the luminescence is due to a lattice defect or impurity that is "poisoned" by near atoms or defects, and the radiation causes the poisoning atom or defect to diffuse away from the emission center.

2.2 Emission Spectrum vs. Radiation Dose

The scintillation emission spectrum was measured during irradiation using the technique described above. A typical emission spectrum is shown in Figure 2. It has prominent peaks at 2.87 and 2.67 eV and smaller peaks at approximately 3.00 and 2.55 eV. A sum of 4 Gaussian shaped emission bands plus a flat background is required to adequately describe the emission spectrum, as fewer bands result in an unacceptable fit. The resulting fit along with its individual components is also shown in Figure 2.

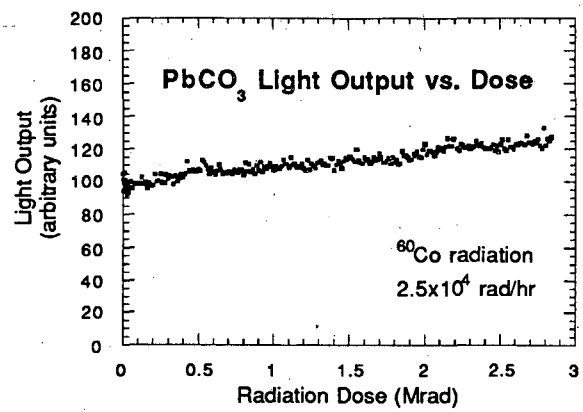

Figure 1: Lead carbonate light output vs. ^{60}Co radiation dose.

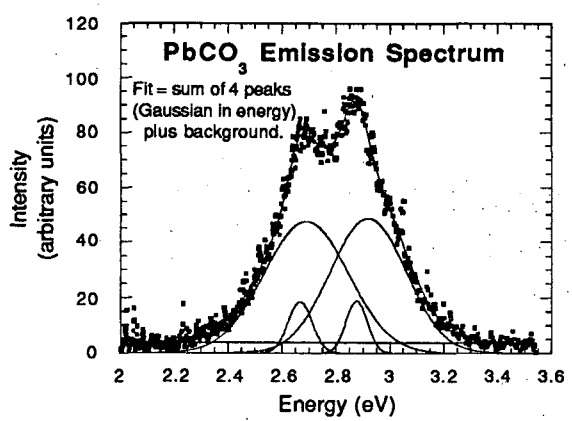

Figure 2: $PbCO_3$ emission spectrum measured during irradiation.

Each of the spectra acquired during irradiation was fitted to the four bands described above, where all of the fit parameters (the peak energy, width, and area of all four Gaussians plus the background level) were allowed to vary. The central energy and width of each of the four peaks remained constant, within the errors of the fit, as a function of radiation dosage. The values for the peak energy and FWHM are 2.91 eV (0.33 eV), 2.87 eV (0.11 eV), 2.67 eV (0.33 eV), and 2.67 eV (0.11 eV). The fraction of light in each of the four peaks (that is, the fit area of each peak divided by the total light output) also remained constant during irradiation (Figure 3). Thus, while the total light output increased by over 25% during the course of the nearly 3 Mrad irradiation, the emission spectrum remained constant.

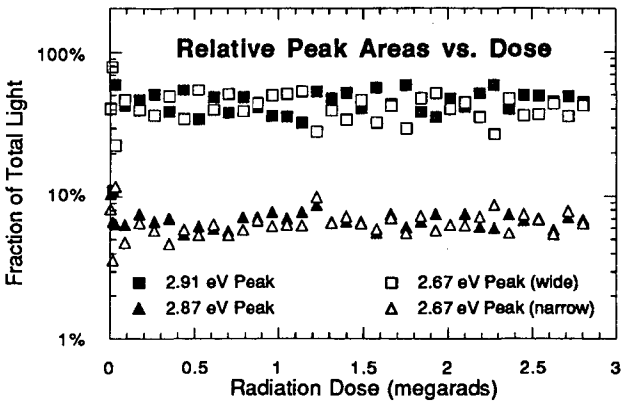

Figure 3: $PbCO_3$ emission spectrum relative peak intensities vs. radiation dose.

3. Temperature Dependence

It was noted in the earlier papers on $PbCO_3$ [1,3] that the scintillation light output depended strongly on temperature. While explicit decay time measurements were not made, observations of oscilloscope traces indicated that the fast decay time component did not change as the temperature was reduced, but a long (1 μs) component appeared [1]. Since it is likely that the optimal operating temperature for lead carbonate is below room temperature, a more accurate measurement the light output as a function of temperature has been made and the decay time distribution has been measured as a function of temperature.

3.1 Light Output vs. Temperature

Since the decay time of $PbCO_3$ is temperature dependent, it is necessary to measure the total light output in a way that is insensitive to changes in the scintillation decay time. This was done by exciting a $PbCO_3$ sample with a 2 mCi ^{68}Ge source and counting the single photon rate with a cooled photomultiplier tube placed 25 cm away from the scintillator.

The sample was contained in a thermally insulated, temperature controlled housing with the source placed next to the crystal. A 2 inch diameter Hamamatsu R-2059 photomultiplier tube was located in a separate, thermally insulated, temperature controlled housing and cooled to –20° C to reduce the single photon dark count rate to less than 1% of the $PbCO_3$ signal at +23° C. A double wall, vacuum insulated fused silica window allowed the scintillation light to pass from the scintillator to the photomultiplier tube while maintaining separate temperature environments. A two inch thick block of lead placed between the source and the photomultiplier tube prevented direct interactions in the photomultiplier tube. The output of the photomultiplier tube was converted to a logic pulse with an Tennelec TC-454 constant fraction discriminator and counted with a Jorway Model 64 CAMAC scaler.

The resulting count rate is shown, as a function of temperature, in Figure 4 after converting to absolute light output by using the previously measured light output of 620 photons per MeV at 23° C. The light output increases at a roughly exponential rate with decreasing temperature until it reaches a maximum value at –125° C, at which point the light output begins to decrease slightly.

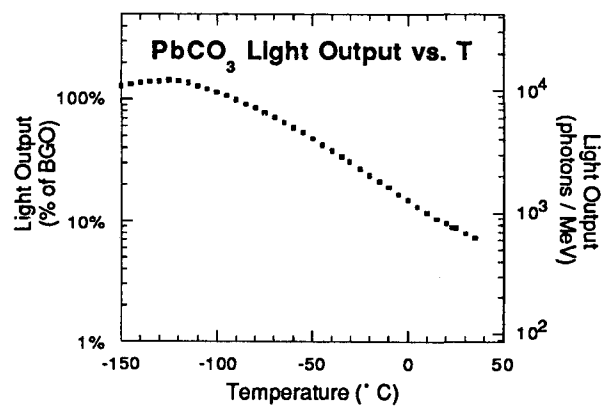

Figure 4: Lead carbonate light output vs. temperature.

3.2 Decay Time vs. Temperature

The fluorescent decay lifetime was measured using the delayed-coincidence method of Bollinger and Thomas [5], as modified by Moszynski and Bengtson [8]. A piece of barium fluoride scintillator coupled to a Hamamatsu R-2059 photomultiplier tube provided a start signal, and another quartz-windowed Hamamatsu R-2059 photomultiplier tube placed 25 cm away from the $PbCO_3$ sample provided the stop signal. As with the total light output measurement, the $PbCO_3$ sample was in a thermally insulated, temperature controlled housing and the single photon photomultiplier tube was cooled to –20° C to reduce dark current. A 10 μCi ^{22}Na source provided the 511 keV photon pairs that excited both the BaF_2 scintillator and the $PbCO_3$ scintillator sample. Timing signals from both photomultiplier tubes were generated using two channels of a Tennelec TC-454 constant fraction discriminator, and the time difference between the start and stop signals was digitized with an Ortec 457 time to amplitude converter and a LeCroy 3512 analog to digital converter.

The decay time of the components extended from 1 ns to above 3 μs. Therefore two timing data sets were collected at each temperature, one with fine timing resolution (0.3 ns/bin) that covered a relatively small dynamic range (600 ns) and one with coarse timing reso-

lution (3.0 ns/bin) that covered a larger dynamic range (6 μs). These two data sets were simultaneously fit with a sum of four exponential decay lifetimes plus a constant background. Two typical timing distributions, with the data binned into coarser bins for clarity, are shown in Figure 5.

A pair of decay time data sets were collected at a variety of temperatures ranging from –140° C to +30° C, and each pair simultaneously fit with the 4 component fit described above. The resulting fit parameters are summarized in Table 1, where the components are numbered in order of increasing decay lifetime and the percentages refer to the fraction of the total number of photons that are emitted with that decay lifetime.

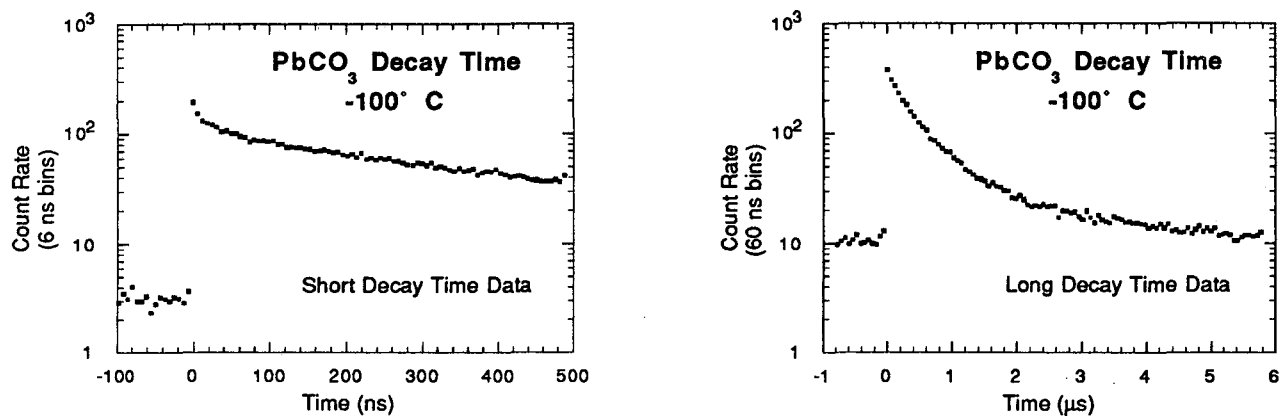

Figure 5: Lead carbonate decay time distribution at –100° C. Data on the left was taken with 0.3 ns bins, data at the right was taken with 3 ns bins. Both have been re-binned for display purposes.

Table 1: Temperature dependence of the measured scintillation properties of natural cerussite. L is the luminescence in photons per MeV, normalized to 8200 photons per MeV for BGO at 25° C, I_0 is the initial intensity in photons per ns per MeV, t_{50} is the time in ns for 50% of the photons to be emitted, and t_{90} is the time in ns for 90% of the photons to be emitted.

T (°C)	L	I_0	t_{50}	t_{90}	Component 1	Component 2	Component 3	Component 4
30	680	47	23.9	467	20% @ 3.9 ns	44% @ 24 ns	26% @ 186 ns	11% @ 1.40 μs
20	818	45	24.0	387	23% @ 5.8 ns	47% @ 32 ns	20% @ 189 ns	10% @ 1.30 μs
10	996	49	27.5	447	14% @ 4.9 ns	49% @ 28 ns	23% @ 140 ns	13% @ 1.24 μs
0	1275	43	31.1	432	33% @ 13 ns	44% @ 58 ns	11% @ 217 ns	12% @ 1.24 μs
–10	1617	41	39.9	466	32% @ 17 ns	41% @ 69 ns	14% @ 191 ns	13% @ 1.17 μs
–20	2019	41	48.6	480	28% @ 20 ns	46% @ 76 ns	16% @ 316 ns	10% @ 1.08 μs
–30	2565	40	63.5	578	28% @ 29 ns	44% @ 93 ns	18% @ 368 ns	10% @ 1.20 μs
–40	3205	37	81.7	657	24% @ 37 ns	45% @ 107 ns	18% @ 359 ns	12% @ 1.07 μs
–50	4011	38	98.3	754	11% @ 32 ns	53% @ 105 ns	18% @ 257 ns	18% @ 1.09 μs
–60	4939	38	132	833	1.3% @ 8.9 ns	43% @ 95 ns	35% @ 257 ns	21% @ 0.94 μs
–70	5989	53	181	1121	0.4% @ 1.0 ns	17% @ 77 ns	62% @ 257 ns	20% @ 1.45 μs
–80	7189	48	227	1263	0.5% @ 1.7 ns	8.7% @ 74 ns	65% @ 268 ns	26% @ 1.24 μs
–90	8347	43	318	1769	0.5% @ 2.2 ns	5.5% @ 72 ns	64% @ 345 ns	30% @ 1.56 μs
–100	9673	56	410	2348	0.5% @ 1.6 ns	3.1% @ 28 ns	60% @ 384 ns	37% @ 1.78 μs
–110	10,780	41	583	2975	0.3% @ 1.8 ns	3.0% @ 32 ns	54% @ 525 ns	43% @ 2.01 μs
–120	11,930	44	823	4665	0.3% @ 1.8 ns	3.5% @ 38 ns	40% @ 539 ns	56% @ 2.71 μs
–130	11,859	47	1040	6004	0.4% @ 1.8 ns	4.9% @ 35 ns	35% @ 590 ns	60% @ 3.35 μs
–140	11,556	52	1004	6185	0.4% @ 1.6 ns	5.1% @ 47 ns	32% @ 440 ns	63% @ 3.36 μs

The variation of the 4 decay lifetimes with temperature is plotted in Figure 6. While it is difficult to accurately measure each lifetime because the fit parameters are highly correlated, the overall tendency is for the various lifetimes to increase with decreasing temperature. A notable exception is tau 1 (the fastest component), which increases until approximately –50° C and then abruptly decreases. Note that Component 4, the long (>1 μs) component that was previously seen only at low temperatures, is actually present in small amounts at all temperatures.

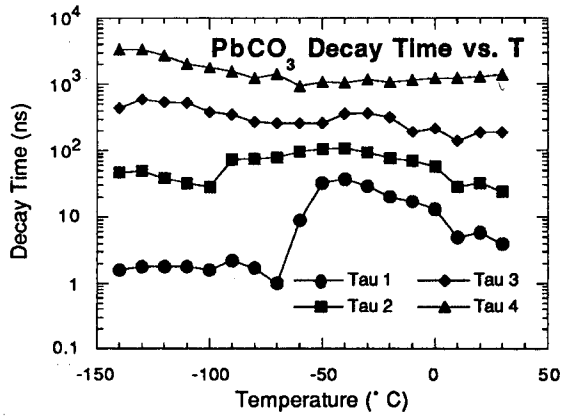

Figure 6: $PbCO_3$ decay component lifetimes vs. temperature.

The relative intensities of each component also vary greatly as a function of temperature, and are plotted in Figure 7. Again, significant correlations between the components are present, but are smaller than the correlations between decay lifetimes. The overall trend is that the majority of the light is contained in the two fastest components for temperatures above –50° C, and the two slower components dominate below –50° C.

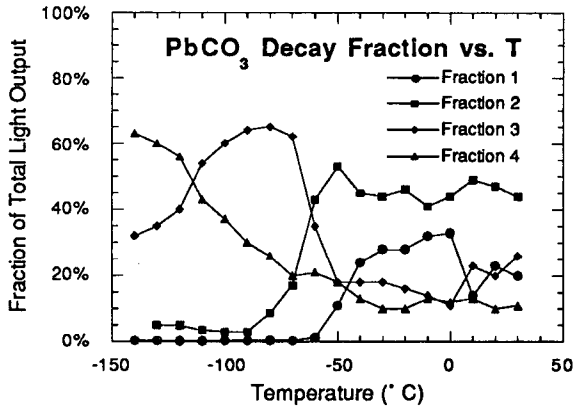

Figure 7: $PbCO_3$ decay component fractions vs. temperature.

It is difficult to determine the optimal operating temperature from the light output and decay lifetime values described above. Therefore we have computed, based on the fit parameters, several measures of the decay time distribution that describe the spectrum in terms that are useful when using scintillators as radiation detectors. First, we compute the initial intensity I_0, which has units of number of photons per ns per MeV of incident energy. This number is useful in estimating the attainable timing resolution of the scintillator. We also compute the times t_{50}, and t_{90}, which are the times that it takes to emit 50% and 90% of the total number of photons. The t_{50} time is useful in estimating the amplifier shaping time, while t_{90} is useful in estimating the dead time of the scintillator. These values are plotted as a function of temperature for lead carbonate in Figure 8 and also are listed in Table 1. For comparison, the values for I_0, t_{50}, and t_{90} for BGO at 25° C are 39 photons per ns per MeV, 160 ns and 590 ns respectively.

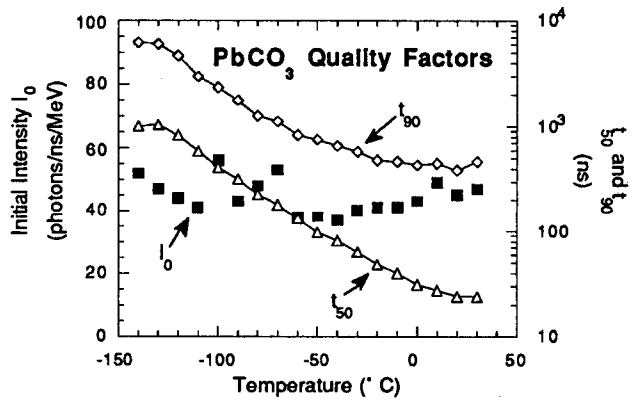

Figure 8: Lead carbonate initial intensity I_0 and times t_{50}, and t_{90} vs. temperature. See text for definitions.

Figure 8 shows that the initial intensity I_0 is approximately 45 photons/ns/MeV independent of temperature, while t_{50} (t_{90}) increases from 25 ns (500 ns) to 1 μs (6 μs) with decreasing temperature. Thus, while the overall increase in the decay time with decreasing temperature increases the amplifier shaping time and dead time of a system using $PbCO_3$, the increasing light output maintains a constant initial photon rate and thus the timing resolution will not deteriorate with decreasing temperature.

4. Purity Dependence

Until recently it has been impossible to obtain synthetic optical quality crystals of lead carbonate. Consequently, the first scintillation lifetime measurements were made with a powdered sample of basic lead carbonate $2(PbCO_3)\cdot Pb(OH)_2$ excited with 22.7 keV x-rays [9] and subsequent measurements were made with an optical quality cerussite crystal [1]. As a result, there

has been some speculation that the fluorescence properties are not intrinsic, but are the result of an impurity. To address these concerns we repeated the x-ray stimulated measurements with powdered samples of high purity lead carbonate, as well as by measuring the scintillation properties of synthetic $PbCO_3$ crystals.

4.1 X-Ray Measurements of High Purity Powders

An accurate measurement of the fluorescence decay time and an estimate of the total light output of a scintillator can be made by exciting a powdered sample of the scintillator with a nanosecond wide burst of x-rays from a synchrotron light source, then observing the emitted light with a photomultiplier tube [9]. The decay time spectrum of each sample is obtained using the delayed coincidence method [5] where a signal synchronized with the x-ray arrival time was generated with a plastic scintillator and a photomultiplier tube [10]. Measurements were made on powdered samples of lead carbonate having different purity and chemical form, namely 99.999% basic lead carbonate $2(PbCO_3)\cdot Pb(OH)_2$, 99.999% lead carbonate $PbCO_3$, and 99.9995% lead carbonate $PbCO_3$. Note that the first sample (99.999% basic lead carbonate) was the compound used in reference [9].

The decay time spectra, shown in Figure 9, are normalized so that the initial counting rate is the same for all three samples. Figure 9 shows that while the overall shape of the curves are similar, the magnitude of the slower components decrease with increasing purity. This change has been quantified by fitting the curves to the sum of four exponential decay components, with the time constant of one component fixed at 1.2 μs, plus a constant background. The results are given in Table 2.

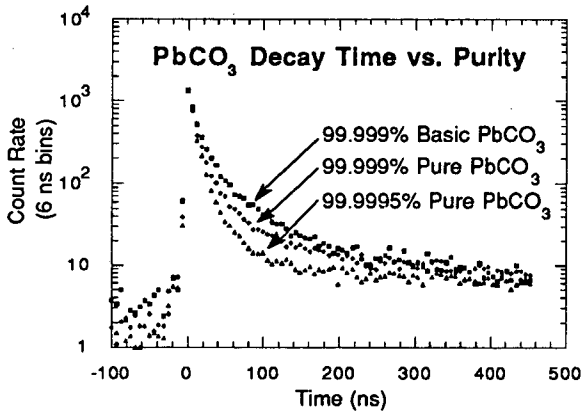

Figure 9: Lead carbonate decay time distribution vs. purity.

Table 2: Decay time fit and light output of powdered sample of lead carbonate.

	99.999% Basic $PbCO_3$	99.999% Pure $PbCO_3$	99.9995% Pure $PbCO_3$
Component 1	26% @ 5.1 ns	19% @ 2.7 ns	22% @ 2.7 ns
Component 2	47% @ 25 ns	42% @ 16 ns	41% @ 12 ns
Component 3	23% @ 118 ns	17% @ 105 ns	10% @ 47 ns
Component 4	4% @ 1.2 μs	22% @ 1.2 μs	27% @ 1.2 μs
Light Output (% of BGO)	8.0%	4.1%	3.5%

Increasing the purity tends to affect the slower components the most, halving both the decay time and fraction of the third component but increasing the fraction of the fourth component. The two fastest components are relatively constant, and so the net effect is to decrease the total light output by removing some of the slow light. This suggests that while the fast light is intrinsic, some of the slow light may be due to impurities.

4.2 Measurements on Synthetic Crystals

The usefulness of lead carbonate as a radiation detector has been limited because it has, until recently, been impossible to grow optical quality synthetic crystals. However Sawyer Research Products, Inc. of Eastlake, OH has recently grown some small (3 mm typical dimension) synthetic crystals of $PbCO_3$. These crystals are quite clear, but have several internal fractures that made uniform light collection impossible. Thus we were unable to detect a 511 keV photopeak, but were able to determine that the scintillation light output was similar in magnitude to a cerussite crystal of similar quality.

The synthetic crystals were luminous enough to measure their decay time distribution at room temperature. The decay time distribution, shown in Figure 10, is fitted by the sum of 3 exponential terms (22% @ 2.0 ns, 69% @ 15 ns, and 9% @ 92 ns) plus a constant background. The signal to noise ratio is not sufficient to measure the fourth (typically 1.2 μs) component. These values, while consistent with the cerussite values, are in best agreement with the fit to the high purity (99.9995%) $PbCO_3$ powder. Again, this suggests that a portion of the slower components may be due to impurities.

5. CONCLUSIONS

The scintillator $PbCO_3$ is quite resistant to radiation damage. It exhibited a 25% increase in luminescence and no change in the emission spectrum after 3 Mrad of ^{60}Co irradiation. During 10 Mrad of irradiation the crystal showed no signs of coloring. The light output and emission time spectrum depend strongly on temperature. The light output increases by a factor of almost 20 as the temperature is reduced from +30° C to the peak emission temperature of –125° C. The decay time tends to increase as the temperature is lowered, but does so in a

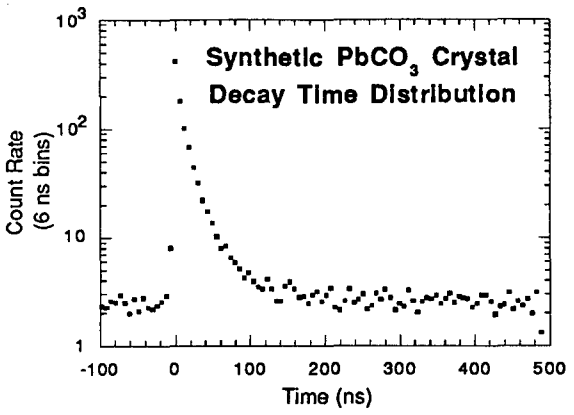

Figure 10: Decay time distribution of synthetic $PbCO_3$.

way such that the initial number of photons per ns is temperature independent. Higher purity powdered samples have a lower light output than less pure samples but the decay times are longer. Finally, scintillation from synthetic crystals has been observed, and, while the optical clarity was not sufficient to observe a 511 keV photopeak, the decay time spectrum at room temperature agrees with the cerussite decay time spectrum.

Further work remains to be performed before lead carbonate can be used as a practical radiation detector. The greatest challenge is to produce large volume, optical quality crystals, and while this promises to be difficult, encouraging progress has been made in the last year. In addition, further radiation damage studies must be made on $PbCO_3$ at a facility capable of simultaneously measuring the luminescence and absorption properties.

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Reference to a company or product name does not imply approval or recommendation by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

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