Inorganic Crystal Scintillators

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Inorganic crystal scintillators find use in many photo detection applications in nuclear physics, high energy physics and PET scanning. This module will compare two crystals, cesium iodide (CsI) and barium fluoride (BaF_2), exploring their characteristics by measuring MeV gamma rays.

This module will use both CsI and BaF_2 crystals, read out by conventional photomultiplier tubes (PMTs). Silicon Photomultipliers (SiPMs) are increasingly used in such applications, but typically do not have a signal-to-noise ratio that compares favorably with conventional PMTs. We have therefore chosen to use the latter in order to place the emphasis on the crystal properties, as well as for orthogonality to other modules.

Cesium iodide, which is slightly hygroscopic, emits light at 310 nm. It is widely used in such applications, either undoped or as CsI(Tl), that is, doped with thallium, which increases the scintillation light output by a factor of 35, but also increases the light decay time by a similar factor. BaF_2 emits scintillation light at two wavelengths, 220 and 300 nm. The 220 nm light has the fastest decay time of any inorganic scintillator (<0.6 ns) and is therefore potentially very interesting for high-time resolution, high-rate applications. The fast scintillation component is, however, only 15% of the strength of the 300 nm slow component, which has a long decay time of 650 ns.

Parameter:	ρ	MP	X_0*	R_M*	dE/dx*	λ_I*	τ_{decay}	λ_{max}	$n^\dagger$	Relative output‡	Hygro-scopic?	$d(\text{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C§
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	-0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	-0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							$<0.6^f$	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(Na)	4.51	621	1.86	3.57	5.6	39.3	690	420	1.84	88	yes	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	310	1.95	3.6^s	slight	-1.4
							6^f			1.1^f		
$PbWO_4$	8.30	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	-2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	-0.2
PbF_2	7.77	824	0.93	2.21	9.4	21.0	-	-	-	Cherenkov	no	-
CeF_3	6.16	1460	1.70	2.41	8.42	23.2	30	340	1.62	7.3	no	0
$LaBr_3$(Ce)	5.29	783	1.88	2.85	6.90	30.4	20	356	1.9	180	yes	0.2
$CeBr_3$	5.23	722	1.96	2.97	6.65	31.5	17	371	1.9	165	yes	-0.1

*Numerical values calculated using formulae in this review.
†Refractive index at the wavelength of the emission maximum.
‡Relative light output measured for samples of 1.5 X_0 cube with a Tyvek paper wrapping and a full end face coupled to a photodetector. The quantum efficiencies of the photodetector are taken out.
§Variation of light yield with temperature evaluated at the room temperature.
f = fast component, s = slow component

This module uses a tabletop dark box that contains the PMTs, crystal scintillators and a collimated ^{22}Na source. It will be necessary to open the box a few times to change out the PMTs and crystals. Please be sure that the SRS high voltage power supplies are turned off before opening the lid of the dark box.

We will explore:

- The rise and decay time characteristics of the two crystals.
- Acquiring pulse height spectra and exploiting the time correlation of the two 0.511 MeV gamma rays produced in positron annihilation in ^{22}Na decay to produce a coincidence spectrum.
- Using the coincidence spectrum to explore the different timing characteristics of the CsI and BaF_2 crystals.

Introduction

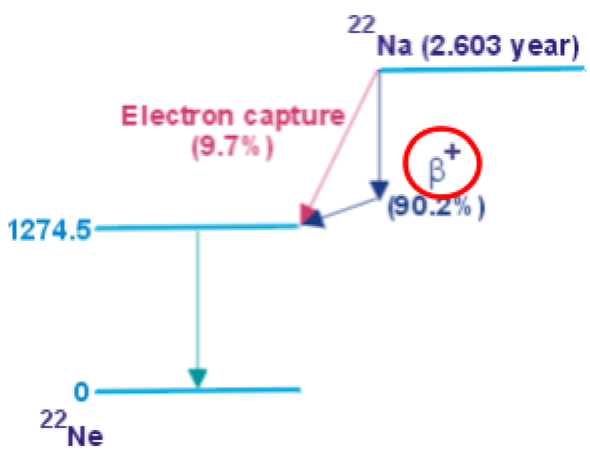


Figure 1. The nuclear level diagram for ^{22}Na

The positrons produced in the dominant decay mode of ^{22}Na annihilate with electrons in the material to produce back-to-back time-coincident 0.511 MeV gamma rays. The electron capture decay mode produces a 1.2745 MeV gamma ray. The singles spectra observed depends critically on the energy resolution of the detector.

Figures 2 and 3 show ^{22}Na gamma ray spectra as observed in a lithium-drifted germanium detector, which collects the charge liberated by gamma interactions in the crystal, compared with that in a thallium-doped NaI crystal scintillator. The substantial improvement in energy resolution of the germanium detector facilitates many measurements, but the use of the charge collection mechanism as opposed to the detection of scintillation light limits the rate capability of the germanium detector.

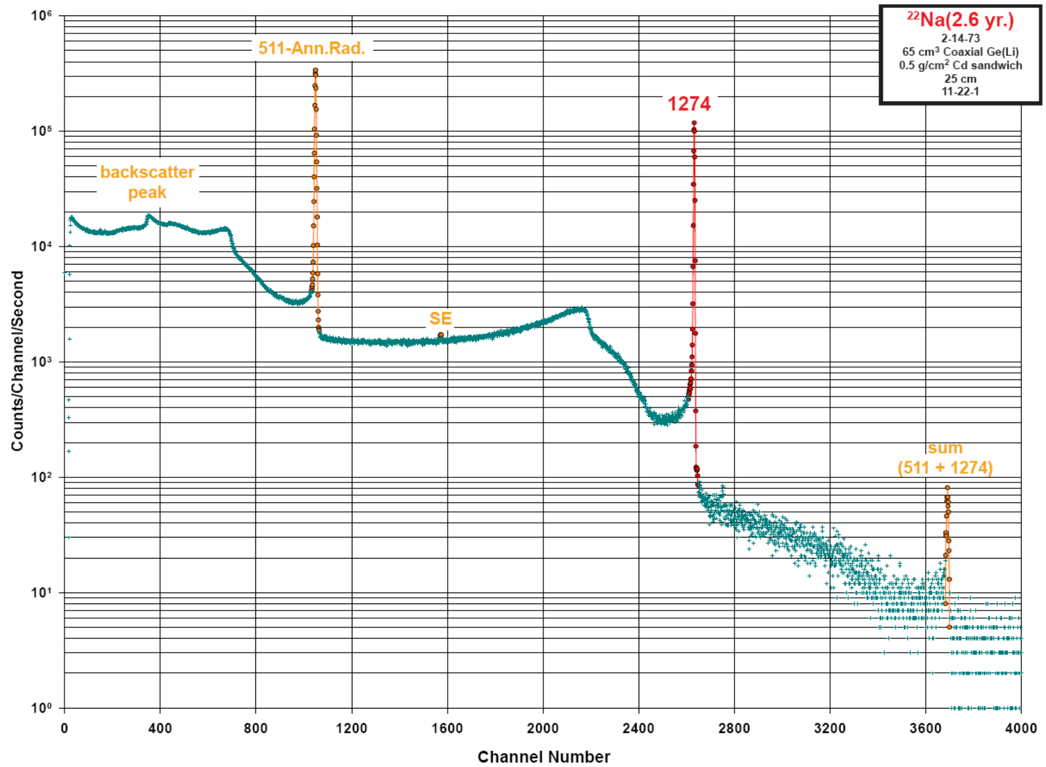


Figure 2. ^{22}Na decay spectrum observed with a large lithium-drifted germanium (GE(Li)) detector.

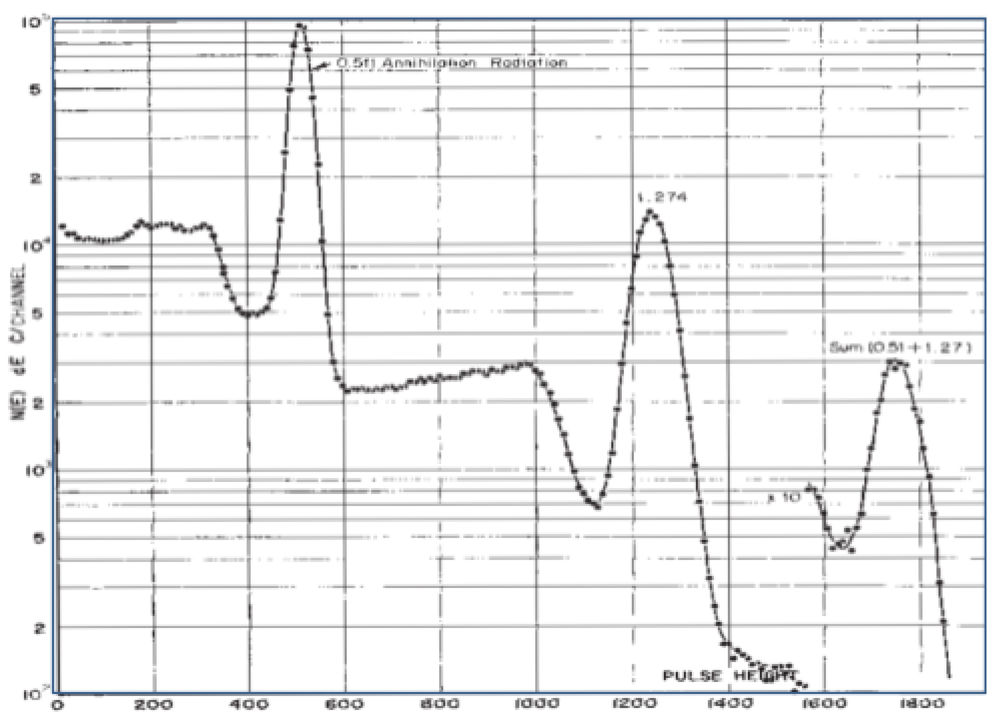


Figure 3. ^{22}Na decay spectrum observed with a large NaI(Tl) detector.

We will use two crystal/PMT assemblies. One consists of a small CsI crystal mounted on a Philips XP2020 photomultiplier tube, serving as a reference. The other will be either a quartz-windowed ET9813QB PMT with a bi-alkali photocathode or a quartz-windowed solar-blind PMT. These will read out different scintillating crystals: CsI, undoped BaF_2 or BaF_2 doped with 5% yttrium (Y).

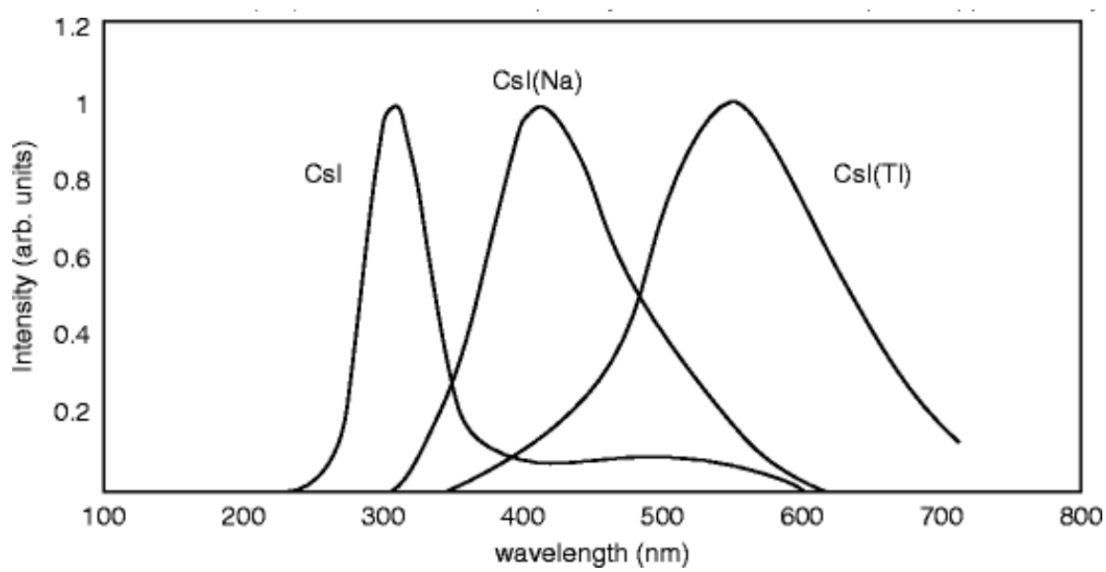


Figure 4. The emission spectrum of CsI and doped (Tl and Na) CsI crystals.

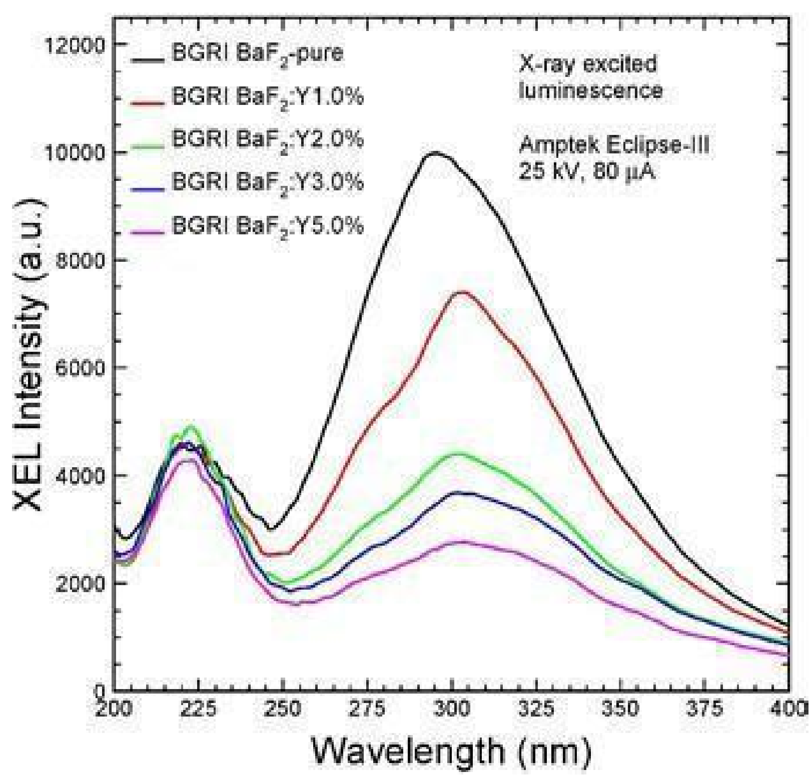


Figure 5. X-ray luminescence spectra of BGRI BaF2 for different Y doping levels; the slow 300 nm component can be reduced with little effect on the fast 220 nm component.

The scintillation light response, seen by a photomultiplier tube, is shown in Figure 6a for undoped CsI and in Figure 6b for undoped BaF_2.

The scintillation light of undoped CsI peaks at 310 nm (Figure 4). The Na and Tl-doped versions produce much more light but have a much slower decay time. The larger component of the undoped CsI crystal we will use has a decay time of 30 ns.

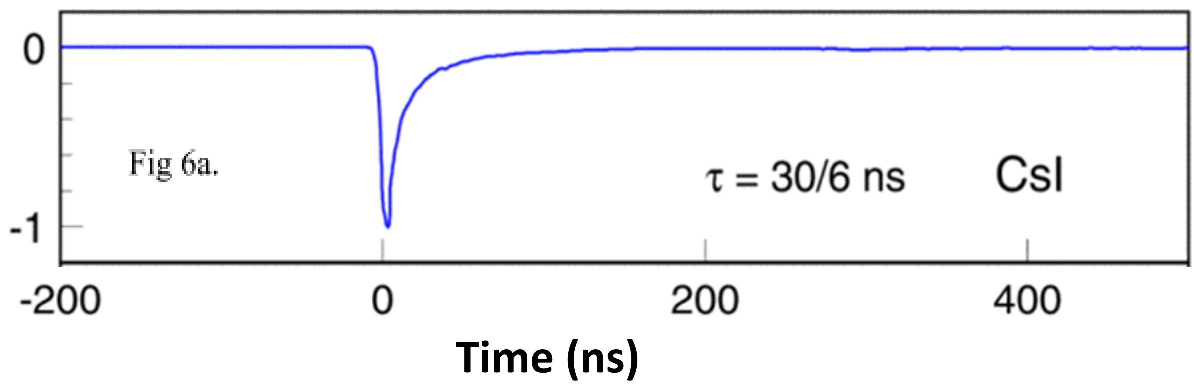


Figure 6a

Undoped BaF_2 has two scintillation light components, at 220 nm and 300 nm (Figure 5). The smaller 220 nm line has the fastest decay time of any inorganic scintillator (<0.6 ns); the larger 300 nm line has a very long decay time of 650 ns.

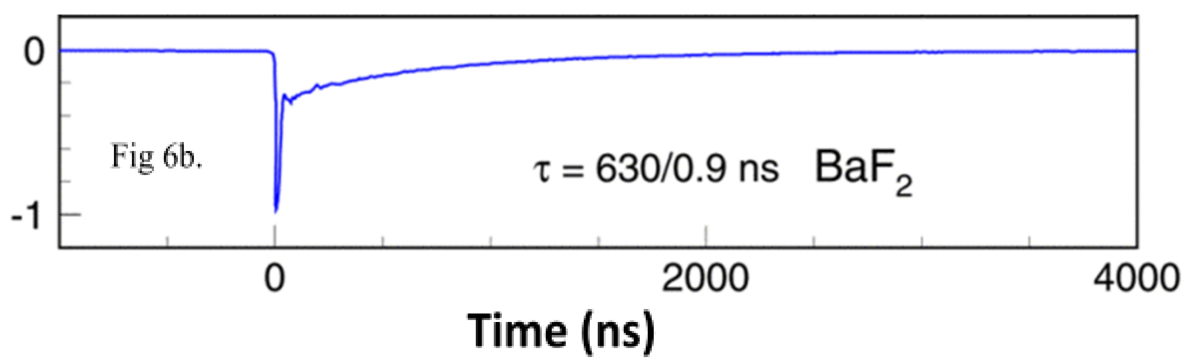


Figure 6b

In order to realize the fast timing and rate capabilities of the fast component, it is necessary to efficiently detect it while ignoring the effects of the slow component. This can be done in two ways, which can be used in combination. The first approach is to dope the crystal to suppress the emission of the slow component. This can be done with several dopants. The most promising is yttrium, as shown in Figure 5. The second approach is to employ a photodetector that is more sensitive to the fast component than the slow component. This can be done with an external bandpass filter, which is typically not very efficient, by incorporating a filter in the structure of a SiPM, which is under development, or by employing a PMT with a so-called solar-blind photocathode, which is the approach we will explore. The quantum efficiency of a Hamamatsu R2059 tube with a quartz window and bi-alkali photocathode and that of a R3197 solar-blind tube are compared with the undoped BaF_2 emission spectrum in Figure 7.

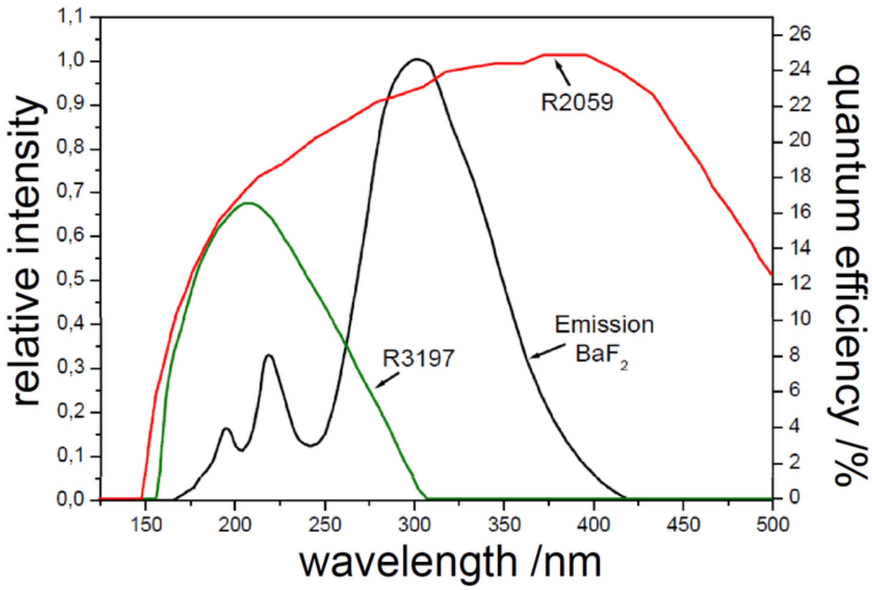
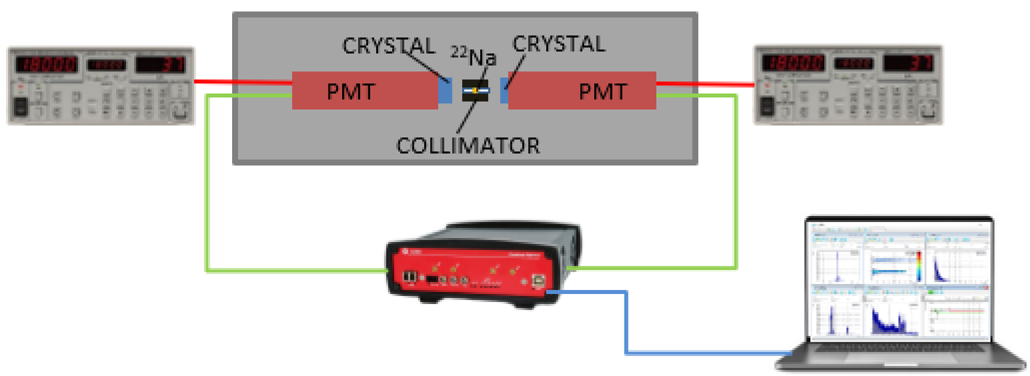


Figure 7. Quantum efficiency of a Hamamatsu R2059 PMT, with a bi-alkali photocathode and a quart window and a solar-bling R3197 PMT, compared to the emission spectrum of BaF_2.

The apparatus



The apparatus consists of three photomultiplier tubes: a glass-windowed bialkali photocathode XP2020, a quartz-windowed bialkali photocathode ET9813QB and a quark-windowed solar-blind Hamamatsu R7818-02, several CsI and BaF_2 scintillators, and a collimated ^{22}Na source. The quartz-windowed tubes are necessary to have adequate sensitivity to the barium fluoride scintillation light in the UV regime. These are contained in a "dark box". There are also two SRS 350 high-voltage power supplies for the PMTs, and a CAEN DT5751 four-channel digitizer attached to a laptop running CAEN COMPASS software.

Activity

Scintillation light of CsI and BaF_2 with PMTs and a ^{22}Na source

The various steps executed in these exercises will use CsI and BaF_2 crystals, with appropriate PMTs to investigate several important crystal properties.

We will first use two 17 mm cubic **CsI** crystals, one mounted on the XP2020 (Side A), and the other on the ET9813QB (Side B) . Given the CsI scintillation spectrum, the response of these two PMTs should be equivalent. The PMTs should be aligned with the collimated source and placed in the dark box. The dark box should then be closed.

a. Connect the PMT signals: Side A to Channel 0 and Side B to Channel 1 of the CAEN DT5751, which is controlled by the CoMPASS software package. Connect the USB cable to the laptop.
b. Set power supply A for the XP2020 bias to 1900V, and power supply B for the ET9813 to 1600V.
c. **DO NOT OPEN THE DARK BOX WHILE THE HV IS ON**
d. Open the CoMPASS program by clicking on the Desktop icon.
e. From the File menu click Open Project
f. Open CoMPASS **Project CsI**
g. Select SCAN to detect the DT5731
h. Start a run by clicking on green arrow in the CoMPASS Plot window
    i. The default settings should be appropriate for this configuration
    ii. By selecting the Settings tab, you can see what the default discriminator levels, number of channels, gain, etc. are. If you are curious, you can change settings to observe their effect.
i. Select the icon New Waveform to observe the Channel 0 and 1 scintillator/PMT waveforms. Compare to Figure 6.a
j. Stop the run.
k. Start a new run for about one minute, and view the New Energy Histogram icon, observing the spectra from each PMT on channels 0 and 1 that show the photopeaks at .511 MeV and 1.275 MeV, together with the Compton scattering features.
l. Click the New PSD icon to see the fast component over total scintillation light ratio. This is not the 6 ns and 30 ns values in Table 1, but rathe due to a a much slower scintillation component do to trace contaminants in the crystal.
m. Set up CoMPASS to require a coincidence of the two channels, and set the energy windows to include only the 0.511 MeV peak. Do this in the Settings tab, then the Trigger/Veto/Coincidence tab by changing the Coincidence Mode to "Paired AND" with default value of 96 ns for the Coincidence window.
n. Click the Time Selection tab and change Correlation to "Paired AND" with the default Correlation window left at 1 microsecond.
o. Click on the "Save project to current folder" to save the settings as the next step has a tendency to make the software crash
p. In the Spectra tab, change the Start/stop time intervals DTmin to -100 ns and the Tmax to +100 ns. You can also change the number of channels for all the plots to

1024.

q. Take a run of three minutes duration.
r. Observe that the energy histogram now shows basically only the 0.511 MeV peak, in both channels.
s. Choose the icon New Energy vs. Energy histogram and observe that the coincidence requirement preferentially chooses the 0.511 MeV energy peaks.
t. Create a filter to only keep the data with energy in the 0.511 MeV energy peak: either use the “define cut” tool in the energy histogram plot, or go to the Rejection tab and manually add the low cut and high cut value. Be sure to then apply the cut.
u. Observe the time-of-flight histogram, and fit a gaussian to measure the time resolution of the pair of scintillators.

1) TURN OFF THE HIGH VOLTAGE

a. Open the dark box.

b. Remove the CsI crystal from the Side B ET9813 PMT and mount the **undoped BaF_2** crystal by sliding its cylindrical mount over the front of the PMT.
c. Close the dark box and turn on the high voltage.
d. Open the CoMPASS Project BaF2
e. Adjust the gate window to 2000 ns, encompassing the decay time of both the fast and slow decay components of BaF_2
f. Repeat step 1k through 1u.

2) TURN OFF THE HIGH VOLTAGE

a. Open the dark box

b. Remove the **undoped BaF_2** crystal from the Side B ET9813 PMT and mount the **BaF_2 crystal having 5% Y doping** by sliding its cylindrical mount over the front of the PMT.
c. Close the dark box and turn on the high voltage.
d. Open CoMPASS Project BaF2Y5
e. Repeat step 1k through 1u.

3) TURN OFF THE HIGH VOLTAGE

a. Open the dark box
b. Replace the Side B PMT with the Hamamatsu R7818-02 **solar-blind PMT** and mount the **undoped BaF_2** crystal by sliding its cylindrical mount over the front of the PMT.
c. Close the dark box and turn on the high voltage.
d. Open CoMPASS Project BaF2_Solar_Blind
e. Repeat step 1k through 1u.