A Proportional counter to Measure the SNO Backgrounds

C. K. Hargrove and Ira Blevis CRPP
and
E. Bonvin Queens University

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Introduction

One of the main contributions to the backgrounds in SNO is from the ^{232}Th and ^{238}U in the D2O. The White Book background estimates are based on 1.1E-14 gm/gm of these isotopes in the the heavy water. The assumption in the White Book is that their daughters are in secular equilibrium. The contribution to the background of these isotopes as updated in the Temple review are shown in Fig.1. It is possible and even highly likely that the various components are not in secular equilibrium and this makes it important for us to work out a way to evaluate the actual contribution of each of the important component daughters to get a realistic estimation of contribution of the individual backgrounds in SNO. This will impact on our ability to calculate and measure both the shape and intensity of the background wall and the neutral current background from photodisintegration of the deuteron.

One of the important procedures that must be developed is a method of calibrating the background wall. The Monte Carlo calculation of each of the main components of the backgrounds from the Th and U chains is shown in Fig 2a and 2b. The calculated shapes and relative intensities of each of these components is quite different and their contributions therefore different. If one measures the shape of each component to an energy well below the upper edge of the background wall one can then attempt to fit the observed shape of the wall with one parameter for each of these components and the well known shape as measured by the calibration. This will also give us a chance to extract their relative intensities if the various components are in disequilibrium. It will provide a check on our chemical methods of measuring the disequilibrium or alternatively to use the measured disequilibrium to fit the background wall.

In this note I describe a simple, accurate and direct calibration source for simulating the contributions to the background wall and the background neutrons in SNO. A small PC with one of the relevant isotopes on the anode can be used to tag the beta decay with negligible effect on the beta's Cherenkov radiation or the resulting gamma ray cascade. One can pick up this resulting Cherenkov light in the PMTs in coincidence with the PC signal with a resolving time of about 10 ns since one will know the position of the source. The source can be used for four purposes.

* Measuring the spectral shape of each of the indiviual contributors to the background wall.
* Measuring the efficiency for seeing a beta-n coincidence in the PMT's of SNO.
* Measuring the neutron production probability by the

^{208}Pb 2.615 MeV gamma ray in the Th decay chain.

* As a general purpose source for looking at the electro-magnetic spectrum of specific radioactive isotopes in the PMT's of SNO.

The main points of this source are:

* The coincidence will allow one to measure the shape of the spectrum well below the background wall down to a few PMT hits.
* Since one can charge the PC with any one of the relevant beta-gamma cascade sources, one can measure each contributor to the background independently.
* At least for the Th chain, one can use the source to detect the neutrons from the ^{208}Tl decay and measure accurately the neutron production probability per gamma ray.
* The PC will cause little distortion of the Cherenkov signal in the PMT's.
* The small size of the counter will make it easy to insert, move around and withdraw from the detector
* It will allow one to work with a relatively hot source since the backgrounds with this good timing resolution will be negligible.

The Proportional Counter (PC) system will be described first. Then each of the above mentioned applications will be addressed in turn.

The Proportional Counter

A prototype PC has been designed and constructed. The PC is the simple cylindrical counter shown in Fig.3. The active region is a 2 cm long by 2 cm diameter thin Al (.018 cm) cylinder. This design is only a prototype. (In a final design in order to reduce the losses of the electron in the counter materials, all the pieces can be made of teflon (n = 1.43) and and the aluminum cylindrical cathode replaced with a thin coating of Al (100 Ang).) It is contained in a lucite tube 1mm thick. The isotope, which will be the source of the radioactivity, will be deposited on the anode which is 20 microns in diameter and made of stainless steel.

The design this prototype is such that the beta particles will lose a negligible amount of energy in the gas, <3keV, and Aluminum, <80 keV. In a final design this latter number can be made completely negligible since the Al can be made as thin as we like by using a vacuum deposition technique. The body of the counter is lucite and the Cherenkov light from the electron in it will closely emulate that of an electron in the water since the refractive index of the lucite and the water are close. (It has been reported to me by Chris Waltham that Dupont make a clear teflon with a refractive index of 1.43 to be compared with 1.33 for water.) A calculation of the effect of lucite, refractive index = 1.5, indicates that 1 mm of normal acrylic, will add a total of 6 photons to the Cherenkov signal of 209 photons in water for a 2.2 MeV electron. The Cherenkov light from the electron in the D_2O after it leaves the lucite will of course be the same as that from the beta in heavy water. Therefore the counter will give an electrical signal from the beta ray and this will be in coincidence with the PMT Cherenkov signal which will closely approximate that produced by a beta ray in the D2O. The gamma rays will be converted mainly in the D2O and will not be affected by the presence of the counter. Therefore the counter will give an electrical signal from the beta ray and this will be in coincidence with a PMT Cherenkov signal which will closely approximate that produced by the beta-gamma cascade in the D2O.

The Spectral Shape Measurements

As mentioned earlier, the Th and U chains have beta-gamma cascades which make significant contributions to the background wall in SNO as shown in Fig. 2a and 2b. There are in fact five isotopes which are expected to make contributions. Each of these will be described. We will emphasize three of them ^234Pa, ^214Bi and ^208Tl since they seem to be the predominate contributors to the background.

The Th Chain Background Calibration

There are three important isotopes which contribute to the background wall in the Th chain. They are ^228Ac with a Q-value of 2.137 MeV, ^212Bi to ^212Po with a Q-value of 2.2 MeV and ^208Tl with a Q-value of 4.99 MeV. Each of these isotopes can be studied by putting the proper parent isotope on the anode wire of the PC. This chain is shown in Fig.4.

^212Bi and ^208Tl

These two isotopes are parallel decay branches of ^212Bi and are therefore considered together. Their contribution to the background wall can be studied with the same isotope on the central wire. The details of the chain are seen in Fig. 4. There are two possible sources. One is ^228Th and the other is ^212Pb.

A ^228Th source will produce all the lower elements of the ^232Th chain with the ^212Bi and ^208Tl beta decays near the bottom. There are five alpha particles per beta-gamma decay which will make the chance rate with this as the parent isotope higher than with ^212Pb as the source. It will however give a very constant rate due to the long half life of the Th. The only decays in this chain which will give a coincidence between SNO and the PC, however, are these two isotopes. The ^212Bi beta decay can be selected by the coincidence between the PC and the PMT's and be tagged by the following ^212Po to ^208Pb decay through its short half life of 300 ns and its highly ionizing alpha particle easily selected in the PC.

The ^208Tl can also be selected by the coincidence between the PC and the PMT's and an anticoincidence with any associated alpha particles. The relative intensity of the Tl and Po branches is well known and their individual measurement in the PC can act as a consistency check on the accuracy of the selection process. The only other beta decay in the chain is from ^{212}Pb. This beta will be seen in the PC but will have no Cherenkov light associated with it because of its low Q-value.

A ^{212}Pb source can be made by depositing the 11h ^{212}Pb on the anode of the PC. This can be done by filling the PC with ^{220}Rn and collecting its daughters by putting a negative voltage on the anode. This will give a source with a 11 hr half life so that the radioactivity will have to be replaced at regular intervals of a few days. However it will only fire on the activities below the ^{212}Pb in the Th chain and this will reduce the singles rate in the counter and therefore the chance coincidence rate.

A summary of the expected rates for all the processes for a ^{212}Pb source are given in Table I. The numbers are based on a decay rate for the ^{212}Pb of 1000 Hz. It is also assumed that the alpha decays can be identified and removed on the basis of pulse height and that the Bi -> Po betas can be removed by identifying the following alpha and by using its lifetime of 300 ns. Table Ia gives the rates for all the interesting processes in the PC and the SNO PMT's and the coincidences between the PC and the SNO PMT's. These processes are identified in the column headings. Table Ib gives the branching ratios and the efficiencies used in the Table Ia. Table Ic gives the chance rates between the PC and the SNO PMT's for the PMT rates as a function of the number of tubes involved in the coincidence.

It can be seen from Table I that the two beta spectra from Bi and Tl can be selected separately and measured with a relatively high rate due to the short resolving time of the PMT's. The rates of a few hundred Hz are easily possible with essentially no chance rate or background down to a threshold of few PMT's.

Efficiency of the SNO PMT's for the Th Beta Branches

If one assumes that one can measure the Bi->Tl->Pb decay chain in the PC with very high efficiency, on can use that to calibrate the PC source strength. One can also, assuming one is using the ^{212}Pb source, use the alpha rate of each branch as a self-consistancy check. From this it should be possible to measure the source strength with very good accuracy. Once one knows the source strength one can then measure detected energy spectrum of each of these branches down to a few PMT hits. Using this information, one can then extract the efficiency for detecting each of the beta gamma branches in SNO as a function of the number of PMT's hit. One can also measure the spectral shape of these branches with arbitrary accuracy.

^{228}Ac

The background spectrum from this isotope can be studied by putting ^{226}Ra on the anode wire. Radium has a half life of 5.8y. It will feed the ^{228}Ac which has a half life of 6.1h and that will feed ^{228}Th which has a half life of 1.9yr. The long life of the ^{228}Th will block any further steps in the chain as long as the source is changed every month. Therefore one can measure with this source the shape of the ^228Ac contribution to the background and its absolute amplitude for a known amount of ^232Th.

The U Chain Background Measurement

There are two important isotopes which contribute to the background wall in the U chain. They are ^234Pa with a Q-value of 2.3 MeV and ^214Bi with a Q-value of 3.27 MeV. Each of these isotopes can be studied independently by putting the proper parent isotope on the anode wire of the PC. This chain is shown in Fig.5. And the contribution in to SNO in Fig 2. After the Tl decay, these two are the most important contributors to the background wall.

^234Pa

This isotope beta decays to the ground state of ^234U with a 1.2m half life and a Q-value of 2.3 MeV. Therefore the background all comes from the Cherenkov light from this single beta particle. This source can be made from either the ^238U parent or the 24 day ^234Th. There will be no further decays of interest since the daughter, 234U, has a life time of 2.5E5 years. The spectrum of decay as measured by the PMT's can easily be measured. The efficiency measurement requires a well calibrated source in the PC.

^214Bi

This isotope with a Q-value of 3.27 MeV is the main beta branch which can cause major backgrounds in the U chain. It can be made by depositing ^226Ra which has a half life of 1602y on the anode of the PC. The total EM energy is 3.27 MeV. The detailed decay chain is shown in Fig. 5. One can absolutely calibrate this chain since its daughter ^nucleus,214Po, decays by alpha emission with a half life of 164E-6 sec. Therefore by observing the coincidence with the PMTs of the ^214Bi decay and looking for the delayed alpha in the PC one can uniquely tag this isotope and select it from the other beta decays. One would produce this source by putting ^226Ra on the anode wire. The decay chain would end with ^210Pb which has a 22y half life.Therefore the ^214Bi decay would be preceeded by two alphas and a beta and followed by the alpha mentioned above.

Measurement of the Neutron Production Efficiency

Since the neutron should be absorbed in the region of the tube, we can put a cut on the neutron position as measured by the PMT's and this will cut down the effective singles rate of the PMT's. For the neutron capture in the NaCl, we have used a factor of 27 for the ratio of the neutron absorption volume in the D2O to the total sensitive volume of SNO and a resolving time of 10 ms. This is equivalent to the neutron capture distance of 2 m. For the PC.PMT coincidence we have used a volume ratio of .5m/6m and a coincidence resolving time of 1.0E-8 sec. If one compares the chance rate to the coincidence rate for the neutrons it will give an idea of the neutron energy cutoff and the resulting detection efficiency one can expect for the system.

The measurement of the neutron production probability using this source is difficult. If one looks at equation 6, one sees that there are a number of efficiencies which have to be known in order to extract this number. One can measure the Tl->Pb-2.6(MeV) PMT spectrum and efficiency by selecting clear PC.n coincidences in which the neutron is uniquely detected. The neutron detection efficiency according to the Monte Carlo is close to 1 at a few PMT hits which we can achieve with this system. That leaves the the neutron capture efficiency to be determined in order to extract the production probability. This may be determined either by an external experiment or by moving the source about within the detector. This latter procedure would make use of the variation of neutron capture with position while assuming that the other factors are only slowly varying functions of position.

There are some obvious conclusions from the numbers in this table:

1. The background beta-gamma spectra can be cleanly measured well below the low energy singles background in SNO for each of the Bi decay branches.
2. The neutron signal can be measured with a reasonable rate and little background in coincidence with the PC with appropriate time and volume cuts.
3. One makes these measurements using the same sources which are causing the backgrounds.

Neutral Current Background

^208Tl

The decay of this isotope is the major source of the neutron background to the neutral current measurement. It is a 36% branch in the Th chain and goes through the 2.615 MeV gamma ray transition in ^208Pb 100% of the time. This gamma ray disintegrates the deuteron freeing a neutron in about one in 500 times. Using the ^212Pb source in the PC or the ^228Th source the rate of this transition can be absolutely calibrated through the measurement of the Bi-Po-Pb decay branch of the chain as described above. One can see the beta part of the ^208Tl decay which will be in coincidence with the PMT's and wait for the the neutron capture in the D2O or the Cl depending on the status of the measurement at the time.

One can even consider the possibility of observing that the 2.615 MeV gamma in this cascade is missing and using this as a signature for the production of a neutron. This is probably difficult to impossible depending on the ultimate resolution of the SNO PMT system because of the small size of the signal in the PMTs. The energy balance in the ^208Tl decay is shown in the following table.

Eb	BR	Eg	Eg-2.6	<Eb>	Eb+Eg +2.6	Eg+Eb -2.6	N Cphot	#Ph
MeV		MeV	MeV	MeV	MeV	MeV	#	Det-b
1.79	.51	3.2	.6	.89	4.09	1.49	53	6
1.5	.21	3.49	.89	.75	4.38	1.64	36	4
1.28	.23	3.71	1.11	.64	4.35	1.75	25	3

The last column gives the number of Cherenkov photons detected on average from the beta particles in the various branches. To get the total number of detected photons one must add the number of photons which come from the associated gamma rays. This can only be worked out in detail by a complete Monte Carlo. What one can say is that the betas will be detected with 100% efficiency in the PC while the beta-gamma coincidences will be detected with somewhat less efficiency. This efficiency will have to be measured to use this coincidence to calibrate the rate of neutron captures.

The rate in the PC and the relatively long neutron capture time in the heavy water will limit the source strength of the PC due to the high chance coincidence rate. With D2O only in the counter and a capture time of 67 ms, a PC event has to be observed in a time window which starts at least 140 ms before the observed neutron capture. This means the mean time between counts in the PC should be >140 ms or a rate in the PC of about 7 Hz. With the NaCl in the counter and a thermalization time of 4.7 ms, this number goes up to about 100 Hz. These numbers are about 1/3 if the beta.PMTs coincidence efficiency is very low for the ^208Tl decay when a neutron is produced. Therefore we would get a tagged-neutron rate of .005 Hz with the D2O and .07 Hz with the D2O + NaCl. It is assumed in this that one can eliminate the singles rates of the alpha pulses on the basis of pulse height, the ^212Bi beta decays on the basis of the fast coincidence between them and the ^212Po alphas. The rate could be increased by roughly a factor of three if one was able to eliminate the ^208Tl beta on the basis of the PMT.Beta coincidence and the ^212Pb betas on the basis ofno PMT coincidences. Of course it is obvious that if one knew the accurate rate at which neutrons were produced by the 2.615 MeV gamma ray one could run the source at any reasonable rate but this is no different from having a simple source with no coincidence.

Neutral Current Background

The ^214Bi decay in the only one that has gamma rays of energy high enough to disintegrate the deuteron. Further only a small fraction, about 2%, of the beta decays go through those gamma ray transitions. Therefore only one in fifty beta transitions produce gamma rays with enough energy and only one in five hundred of those will produce a neutron. That is only one in 25,000 beta decays will produce a neutron. Therefore it would be very difficult to use this source to measure the neutron background. It may, however, be possible to tag the neutron production since in this case the EM spectrum in the PMTs will be missing the 2.445 MeV which will be absorbed by the photodisintegration process in the D2O. This will leave only .825 MeV of EM energy to be detected by the PMTs. It will be very difficult if not impossible to observe this energy in the PMTs. Therefore the only way to associate a neutron with the PC is to look for the singles in the same times windows as mentiooned above. This means the neutron rate in coincidence would have to be almost impossibly low.

Comparison with non-Coincidence Sources

One could do much of this measurement by putting an appropriate source of the background in the counter and looking at the spectrum of this in the SNO PMT's. There is some saving in hardware by doing this and so it is worthwhile comparing the this method with the PC method.

1. The PC method allows one to calibrate the source intensity as one is using it and one does not have to rely on an external calibration.
2. One can measure the spectrum of the beta-gamma cascade associated with the neutron capture. This might be useful in actually detecting when one has a neutron produced by the background as distinct from a neutrino.
3. The source strength can be kept much smaller since the coincidence will allow us to go to a low number of PMT hits with only a weak source.
4. The neutron production and capture rate will be measured with the source that is producing the neutrons.
5. The coincidence will guarantee that the source will be producing the signal which we are measuring.

Other Sources

40K

This source could be used in the counter. It decays by either K capture (10.7%) or beta decay (89.3%) with Q-values of 1.505 MeV and 1.311 MeV respectively.One could look for the Cherenkov light assoociated with the beta decay branch and measure the spectrum associated with this decay in the PMT's.

^24Na

This isotope decays with a half life of 15 hr and a Q-value of 5.513 MeV. It has a 99% branch which goes through 2.75 and 1.37 MeV gamma-ray cascade. One could use this source to measure the neutron production probability for the 2.75 MeV gamma ray and its associated spectrum in the PMT's.

^252Cf

This isotope has a well known fission branching ratio of 3% and produces 3 neutrons per fission. Such a source on a counter would be useful as a tagged-neutron source. The fissions wold be readilytagged through the large amount of energy produced by the fission and also the gamma-ray energy released by the fission products in the PMT's.

Program

A prototype counter, shown in Fig. 3, has been constructed in the STC here at Carleton. Preliminary tests of this counter have been carried out and some preliminary results obtained. In particular the central wire has been activated with 228Th. Then the counter has been looked at with a digital oscilloscope which has also had a NaI(Tl) scintillator, placed close to the PC, put into a second input. With this setup we have been able to observe the alphas and betas of the Th decay chain. We have also observed the beta-alpha decay chain ^212Bi->^212Po->^208Pb, Fig. 6. We have also observed the ^208Tl beta in the PC and a gamma ray in the NaI(Tl), Fig 7. This shows the viability of the system to measure both parts of this chain. Our next step is to make these measurements quantitative and measure the efficiency of the PC and our ability to make detailed measurements on the rates in the counter. Finally, we plan to put the source in water and look for the Cherenkov light in coincidence with the PC in a SNO PMT.

There will need to be further checks on the design. In particular one will need to study the connector assembly and the method of depositing the Th and U on the anode wire. The former will have to be water-tight. The latter will require of deposition which will not change the gain properties of the wire. Further, it is well known that the Th/U would tend to migrate around the counter. Therefore it would be necessary to put a thin coating of gold or some other material to fix the Th/U position.

Budget

An initial budget of $5,000 would be required to manufacture the tubes and do the testing of it. This would include the cost of materials and labour in the shops and some equipment to carry out the testing program.

To summarize, this source can be used for five purposes:

1. To measure the shape of the Th/U background spectra. The Cherenkov light can be detected in the SNO PMTs and selected by a coincidence signal between it and the signal in the PC. In this way one can pick out the shape of spectrum well below the upper edge of the background wall and quantitatively determine its shape.

2. To calibrate the neutron production probability of the Th chain in SNO. Since about one in every 500 of the 2.615 gamma rays in ^208Tl decay will produce a neutron, one can detect the neutron and then look back in time for the beta-PMT coincidence. This method of identifying the PC event and the neutron capture event can be used measure the Tl neutron capture probability.

3. To measure the neutron response in SNO. Once one

knows how many neutrons the source produces, it is then possible to use this as a source to calibrate the neutron response of SNO as a function of position.

4. To put a constraint on the number of background neutrons being produced by the Th chain contamination. Once one has measured the contribution of Th to the background wall, one has a constraint on the the number of background neutrons being produced in SNO.

5. As a general purpose source for tagging a number of useful background and neutron calibration sources.

Table Ia

The SNO PMT PC Rate Sheet

RATES in HZ	Singles Beta	Singles Alpha	Coinc PC.PMT	Coinc PC.PMT -2.615	n-Prod	n-Detect	Coinc PC.PMT.n
ISOTOPE DECAYS							
^212PB	1000						
Bi->Po	640		448				
Tl->Pb	360		324	72	0.72	0.538	0.11
Bi->Tl		360					
Po->Pb		640					

Table Ib

Pb decay Rate	B R Bi->Po	B R Bi->Tl	Bi->Po PMT Eff	Tl->Pb PMT Eff	Tl->Pb PMT Eff -2.615	n-Prod Eff
1000	0.64	0.36	0.7	0.9	0.2	0.002

PMT n-Det Eff	Eff. n-Capt
0.9	.83

Table Ic

# of PMTS	10	15	20	25	30
RATE of PMTs	12.68	0.95	0.032	0.005	0.0001
Chance PC.PMT.n	0.68	0.051	0.0017	0.00027	5.3E-06
Chance rate-PC.PMT	1.0E-7	7.5E-9	2.5E-10	3.9E-11	7.5E-13

Vol Ratio (assume 2m) 0.03704
Coincidence time(n) = .01 sec
Coincidence time(PC.PMT) = 1.0E-8

The Formulae used to calculate these rates are as follows:

The Efficiency of the PC is always assumed to be 1.0 so that all efficiencies used here are for the PMT's seeing the relevant EM radiation.

R(PC.PMT(Bi->Po)) = R(^212Pb)*BR(Bi->Po)*Eff(Bi->Po) 1.

Here
R(PC.PMT(Bi->Po)) is the observed coincidence rate for Bi->Po decay
R(^212Pb) is the parent ^212Pb decay rate.
BR(Bi->Po) is the branching ratio for the named decay branch.
Eff(Bi->Po) is the efficiency of the PMT's for seeing the electromagnetic energy of the decay.

R(PC.PMT(Tl->Pb)) = R(^212Pb)*BR(Bi->Tl)*Eff(Tl->Pb)   2.

R(PC.PMT(Tl->Pb-2.6)) = R(^212Pb)*BR(Bi->Tl)*Eff((Tl->Pb)-2.6)   3.

R(n-Prod) = R(^212Pb)*BR(Bi->Tl)*P(n-prod)   4.
where P(n-prod) is the neutron production probability for a 2.6 MeV gamma ray.
R(n-Detect) = R(^212Pb)*BR(Bi->Tl)*P(n-prod)*Eff(n-capt)   5.
*Eff(n-detect)
R(PC.PMT.n) = R(^212Pb)*BR(Bi->Tl)*Eff((Tl->Pb)-2.6)
*P(n-prod)*Eff(n-capt)*Eff(n-detect)   6.
where Eff((Tl->Pb)-2.6) is the efficiency for seeing the Tl->Pb decay in the PMT's when the 2.6MeV gamma ray has produced a neutron.
Chance(PC.PMT.n) = R(^212Pb)*BR(Bi->Tl)*(Eff((Tl->Pb)-2.6)
+ Eff((Tl-Pb)E<1.5MeV))*R(PMT)*(dV/V)*RT   7.

Fig Captions

Fig. 1 The expected rates for 1 year in the SNO detector from the various sources.
Fig. 2a The calculated background rates for 1 year for each of the contributions from the Th and U chains over the high energy range.
Fig. 2b The same as 2a except it covers a lower energy range.
Fig. 3 A line drawing of prototype design of the proportional counter.
Fig. 4 The Th decay chain
Fig. 5 The U decay chain
Fig. 6 A digital oscilloscope plot of the beta alpha decay chain showing the small beta pulse preceding the large alpha pulse by about 160 ns.
Fig. 7 A second oscilloscope plot showing the beta particle (trace 2) in the PC and one of the gamma rays seen in coincidence wih it a NaI(Tl) counter (trace 1).