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Simultaneous NC, ES, CC Solar-neutrino Detection using Salt-filled Bladder with SNO

R.B. Schubank, U.B.C.
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Abstract

A Proposal for SNO is made for simultaneous detection of Neutral Current, Charged Current and Elastic Scattering of Solar-neutrino induced events. The detector would be a thin (order 0.001"), flexible, transparent bladder, of radius 5m to be placed within the main 6m radius acrylic sphere. It would be filled with heavy-water containing the usual 2.5T dissolved NaCl to act as the neutron-to-electron converter. Up to 50Kg of HBO_3 would then be added to the region of heavywater between the main shell and the bladder in order to quench background neutrons from gamma induced fission of the deuterium from radioactivity in the main acrylic shell, PMT's and support structures and the lightwater. The light water region outside the main shell would be sensitive to ES signals, the heavywater region between the shell and the bladder to both ES and CC, and the region inside the bladder to ES, CC and NC. The detector could be inserted or removed at any time during the operation of SNO. In the unlikely event of rupture of the bladder SNO would still remain operational as only the NC signal would be quenched, but only for the length of time required to remove the HBO_3 and/or NaCl from solution.

To date, there have been several proposals [1,2,3,4,5] made to measure all three components, Elastic Scattering, Charge Current and Neutral Current, of the solar neutrino spectrum. Particular emphasis has been placed upon extracting the NC, as ES and CC are the "default" signals. These include:

a) simple foreground (D_2O) / background (H_2O) + Monte Carlo

b) suppressing NC with HBO_3, where the ^{10}B in the salt captures neutrons from the NC and creates nondetectable alpha particles.

c) addition of 2.5T NaCl to the heavywater to convert NC to high-energy gammas which Compton scatter to high energy electrons

d) addition of 5Kg Gd to the heavywater to convert neutrons into high-energy electrons

e) installing an array of order 200 ^3He proportional counters of dimension 2.5cm diameter by 1m, with separate electonic readout

f) addition of 5Kg Gd (or isotope separated Gd) to the acrylic shell to localize the NC signal from ES and CC signals

g) installing ^{10}B or ^6Li loaded scintillators

There are several drawbacks with each of the above methods:

- Separate detection schemes, such as e) and g), suffer from overwhelming background due to radioactivity in the materials used in construction, since the radioactivity is counted in both primary (alpha and beta decay) and secondary (gamma fission of surrounding heavywater) forms. Also, the matrix of detectors may have a detrimental impact on ES and CC by absorbing or rescattering a significant proportion of the photon signals (the ^{3}He counters will need a thin Cu layer to act as an outer electrode and to prevent diffusion of the 3He out of the counter). It still remains to be seen whether or not suitably low levels of radioactivity can be achieved for the 3He counters;[6] they most certainly cannot be met with ^{10}B or ^{6}Li loaded plastic or liquid scintillators.

- Since the acrylic shell is a major source of localized radioactivity, expressing itself mostly as gamma induced deuterium fisson neutrons from 2.5MeV gammas from U/Th decay chains, plus a small high energy gamma component from ^{214}Bi/^{208}Tl daughters, f) is feasible only if the target purity levels of U/Th of a few ppt can be achieved; since this would appear unlikely by at least an order of magnitude, and since once installed the Gd cannot be removed or "turned-off", this method must also be rejected.

Methods a) to d) require separate foreground/background measurements and are thus insensitive to temporal variations in neutrino flux such as anti-correlation with sunspot activity or even supernovae. In a) and d), the NC is only poorly detected compared with c), with substantial reliance on Monte-Carlo and NC suppressing by b) to unfold the spectral components. The acrylic induced backgrounds still remain to plague the experiment by further requiring a factor of two reduction of fiducial volume, from 1000m^3 to 500m^3, for the NC as well as ES and CC; full volume for ES and CC is available only when the NC is quenched using HBO_3.

The Bladder

To overcome the handicaps of not being able to simultaneously monitor all three neutrino induced signals and the difficulties from background contribution of the acrylic sphere we hereby propose to insert a transparent, impermeable bladder of 5m radius into the main 6m radius acrylic sphere. The active NC-neutron converter will be the normal 2.5T of NaCl; the "inactive" background-neutron quencher will be up to 450Kg (probably much less will be required) of HBO_3 added to the region between the sphere and the outside of the bladder. A schematic of the bladder in relation to the SNO detector is shown in Figure 1.

Ideally, the bladder should be: [7,8]

a) transparent to light from 300 to 600nm. Most transparent plastic materials contain a UV inhibitor to protect against UV-induced breakdown; however, it is possible to specify UVT, i.e., without the UV blocking additive. Because the material will generally have an optical index of refraction of 1.5, compared to 1.33 for water, there will be an average "loss" of 2-4% at each bladder/water interface, or 4-8% total; however, much of this light is reflected. It should be possible to incorporate scattered photon hits in the secondary event-reconstruction algorithims.

b) low haze; haze is defined as the % deviation from straight transmission, due to scattering within quasi-crystalline structures in the plastic and/or surface blemishes. For comparison, a 40cm diameter PMT at 8.5m subtends 5%, so the contribution from <2% ("low") haze is negligible.

c) flexible, to facilitate installation and removal

d) chemically inert, especially to water, NaCl and HBO_3

e) impermeable to water, and most importantly, Cl and B ions. This generally means using plastics such as polyethylene (CH_2), polypropylene (C_3H_6), both with and without saran coating, polyvinyl-chloride (PVC), and ethylene-vinyl-acetate (EVA). The above materials are up to 200 times less permeable to direct water and/or water absorption (swelling) than the polymethyl methacrylate (acrylic) used in the main shell. Rubbers generally tend to swell too much (few to tens of %) to be of use; however,a synthetic rubber, ethylene-propylene-diene monomer ternary copolymer (EPDM) may also show some promise.

f) low radioactivity levels; generally expect few ppt U/T, cf 4/2ppt (x10? [6]) for the main acrylic shell

g) thin (order 0.025cm or 0.001"): this aids in light transmission, flexiblity and total radioactivity. Even if radioactive isotope levels are a factor of 10 times higher than ideal for the acrylic (which seems to be more likely, given the conservative results of acrylic samples to date coupled with residues from imbedded norite dust during assembly of the acrlyic), the total contribution from the bladder would still be 200 times smaller than the main shell.

h) strong and tear resistant. If 2T of NaCl were to be placed inside the bladder and non outside, then the bladder would have to be capable of supporting the entire 2T weight; this source of stress could be reduced or eliminated by adding an appropriate amount of NaCl to the region outside the bladder to achieve neutral bouyancy. The bladder must also be able to withstand the stresses from insertion into and removal from the main acrylic shell.

i) good folding endurance (both optical and physical), again because of insertion/removal requirements

j) constructable using present technology. The material would most likely be manufactured in the form of sheets. Some companies [9] already possess the skill to assemble large, leaktight, thin spheres with several different materials, using mold-forming, heat-welding, ultrasonic-welding and other techniques.

We are currently collecting UVT samples of CH_2 (cold-quenched,low haze [7]), plasticized C_2H_6 with and without saran coating, EPDM, EVA, and PVC for optical testing, since most readily available references in the literature do not list specific (or even general!) optical transmission, reflection and absorption coefficients with photon frequency. Table_I lists some of the physical properties of the above flexible and transparent plastics, including acrylic for comparison.

Table I [8]

	polymethyl methacrylate	CH_2 low	CH_2 med	CH_2 hi	C_3H_6 extr.	C_3H_6 oriented	EVA	PVC (plast)
Processing Method	orientation/ extrusion		extrusion		extr.	oriented /saran	extr.	extr.
Specific Gravity	1.18 / 1.14	.91	.93	.95	.89	.905	.94	1.2-1.8
BurstingStrength Mullen pt. per 1mil	--- / 35-40	10-12	---	---	---	---	10-12	20
Tearing Strength g/mil	--- / ---	100-500	50-300	15-300	600 TD	7-10	50-300	60-1400
Folding Endurance	--- / 1500	Excel.	V.high	V.high	V.high	Excel.	V.high	---
Water Resistance Rating	Good / Good	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.	Excel.
Water Absorption 24hr, %	.3-.4 / 1.4-1.6	<.01	<.01	<.01	<.005	<.005	<.01	negl.
Rate of Water Vapor Transmission per 24hr $g/100in^2/mil$ @37.8C	1.0 / 8 (3mil)	1.0-1.5	.7	.3	.7	.4	14	4-20
Permeability CO_2	--- / ---	2700	2500	580	800	370 /---	6000	100-3000
$cc/100in^2/mil$ H_2	— / ---	1950	1950	--	1700	--- / ---	---	---
/24hr/atm N_2	--- / ---	180	315	42	48	— / <1	400	---
@25'C O_2	--- / ---	500	535	185	240	120 / <1	840	30-2000

Neutron Response

For the conventional SNO configuration [2] with 1000T D_2O plus either 0 or 2.5T NaCl, 6.8% / 24% of neutrons produced by gamma activity originating in the acrylic sphere are absorbed, with 68% / 95% of those inside the sphere absorbed within the first meter. The attenuation gammas above 2.2 MeV reaches a factor of 200 after the first meter; this is approximately the same level as would be contributed to by a 5m radius, 0.001" thick bladder with 10 times greater U/Th concentration than the desired level for the acrylic! The amount of NaCl in the first meter from the shell is 1.05T; an equivalent quantity of ^{10}B to quench by the same amount is 9Kg, or 5Kg as HBO_3. The fraction of neutrons uniformly generated within the entire volume of 6m radius with the normal NaCl that escape the sphere is 14%; the fraction generated in the first 5m that escape beyond 5m is also approximately to 14%, as "no decrease in the capture distribution is observed [with Monte Carlo] inside a 5.5m radius" [2]. By doubling the concentration of NaCl, the fraction of escapes is only reduced to 10%. Therefore, by adding up to 10 times the equivalent mass of ^{10}B, or 50Kg of HBO_3 (depending on the level of U/Th contamination) to the region between the 5m radius bladder and the 6m radius acrylic shell (and topping up with with 1000Kg of NaCl to maintain neutral bouyancy of the bladder), the acrylic gamma-neutron background could be effectively quenched. The simultaneous measure of separate Charge-Current, especially at the lower energies, becomes quite feasible. The only expense would be a 42% reduction in NC volume to 579T, but this would be the case anyway due to the necessity of software cuts to the same volume for the conventional run.

A further increase in the concentration of NaCl would not be warranted, due to the greatly diminished improvment in probability of neutron conversions resulting in gamma energies >6.5MeV: no NaCl gives 24% probability, 2.5TNaCl/1000T D_2O gives 53%, but 5T NaCl/1000T D_2O gives only 55%.

Impact on Water Purification and Support Structure

Ideally, three separate water purification systems, one for each layer (H_2O, D_2O+HBO_3, $D_2O+NaCl$), would be desired; however, it should be possible to get by on as little as two. The H_2O region most certainly needs continuous cleaning because it is in contact with surfaces, such as glass, stainless-steel, and coated/anodic aluminum, that slowly leach undesirable material into the light water. Once each of the two heavywater regions have achieved maximum purity, it may no longer be necessary to continue purification as as steady proccess; rather, one system could be "shared" in sequence between either region, in perhaps intervals of 6 months, with adaptation for the HBO_3, which is otherwise easily removable with conventional ion-exchange. The periodic full purification is still warrented in order to remove buildup of Rn, Tl, Bi and other daughters in the U/Th decay chains.

Effects of leaching of radionuclei from the main acrylic shell into the outer D_2O+HBO_3 region will tend to be suppressed by the presence of the HBO_3, acting both as a neutron absorber and as a mild biocide. Because of the bladder's low mass and thickness, the leaching of contaminants from the bladder into the central $D_2O+NaCl$ region should be small to begin with, and would probably diminish in time to reach the equilibrium levels of the heavywater.

The buildup of boron that crosses the bladder into the central region would have to be modelled and in real operation, carefully monitored, as it could begin to compete with the NaCl for neutrons if concentrations were allowed to sufficiently climb. Fortunately, boron is easily removable, so if the permeability of boron through the bladder proves to be unacceptably high, then a simplified purifier, rather than the more complicated one, could be used to continuously remove the boron from solution.

The bladder support structure must be capable of supporting the bladder itself with any differential weight due to salt imbalances in/outside the bladder, the plumbing system connecting the bladder to the water purification and filling system, and allow for insertion and removal of the bladder to and from the main acrylic shell. This should be a straightforward engineering task.

Options

One option would be to use 5Kg of Gd instead of 2.5T of NaCl as the active neutron converter. Although Gd has already been evaluated by Monte Carlo, [2] a serious flaw exists in the modelling of the Gd neutron-capture gamma energy distribution, which detrimentally biased the results against use. (Fortunately, the gamma decay scheme of Cl is much simpler and so it was treated exactly.) While it is true that the mean number of emmited gammas per neutron capture is 3.4, with a total energy of 8MeV, the total energy is NOT at all uniformly distributed! The primary gamma in every Gd cascade has a minimum energy of 4.0 MeV (or more, depending on the whether the isotope is 155Gd or 157Gd), with an average of 6 MeV for the primary. It is the energy distribution of the primaries, which ranges from 4 to 8 MeV, that is more or less uniform! The secondaries, tertiaries, etc., take up the remaining 0 to <4 MeV. (Furthermore, multiple Compton scattering for an individual gamma may not have been taken into account).

Conclusion

It has been shown that a 5m radius, salt-filled, transparent bladder, which would probably be constructed of 1mil low-haze / cold-quenched / UVT polyethylene, could be of significant benifit to SNO by allowing simultaneous extraction of all three neutrino-induced signals, ES, CC and NC, as well as have a positive impact on the effect of background signals from radioactivity in the main acrylic shell. The proposal should warrent a full Monte-Carlo investigation. Furthermore, the impact of using Gd-salt instead of NaCl should be looked into again not only in conjunction with the bladder, but also by itself.

References

[1] "SNO Proposal", SNO-87-12 ("White Book") Oct. 1987; sections on ES, CC and NC

[2] "SNO Collection of Annexes in Support of the Main Proposal", Nov. 1987:
#1 "Calculations of Neutron Transport in the SNO Vessel", E.D. Earle and P.Y. Wong

#6 "A Monte Carlo Simulation of the SNO Heavy Water Cerenkov Detector", R.C. Allen, G. Buehler, H.H. Chen, H.-B. Mak and K. Roemheld

#7 "Simulation of the SNO Heavy Water Cerenkov Detector Response to Low Energy Phenomena", R.C. Allen, G. Buehler, H.H. Chen

[3] "Update of SNO Proposal", June 1988; sections on ES,CC and NC detection

[4] "Scientific and Technical Description of the Mark II SNO Detector" Ed. by E.W. Beier and D. Sinclair, SNO-89-15, Oct. 1989.

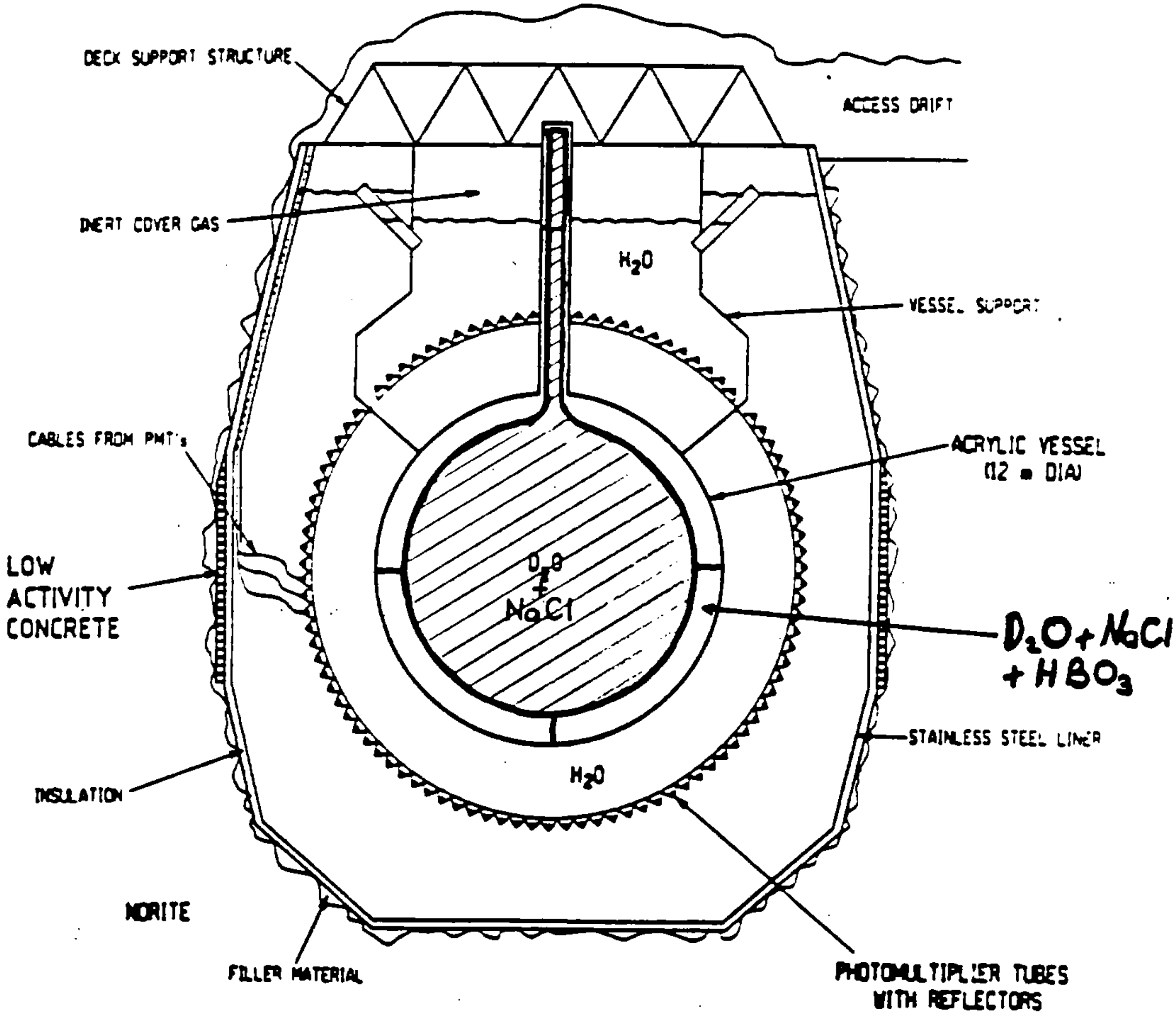
[5] "Gd in the Acrylic Shell as on online neutron converter for SNO", Oct. 1989, R.B. Schubank and C.E. Waltham

[6] private communications

[7] "Plastic Materials", J.A. Brydson, (Butterworths Press),TP1120.B7 1989, sections on acrylic, CH2 (esp. p225), C3H6, diene rubbers, PVA, PVC, styrenes, etc.

[8] "Guide to Plastics", by ed. of Modern Plastics Encyclopedia, (McGraw-Hill, Inc.) TP1120.G853 1970, pp66-85,126-130

[9] private communications with "B.C. Inflatables", Burnaby B.C. / "Inflatable Images", Edmonton, Ata.



CROSS SECTION OF NEUTRINO DETECTOR

FIGURE 1. SALTY BLADDER IN SNO