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^{16}N : A Calibration Source for SNO

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ABSTRACT

The 6.13 MeV γ-ray following the β-decay of ^{16}N ($t_{1/2}$ = 7.13 s) can be used for an absolute light or "energy" calibration of the Sudbury Neutrino Observatory [SNO] detector. We propose to produce this source by the ^{16}O(n,p)^{16}N reaction. The fast neutrons would be produced by a D-T generator. The short-lived ^{16}N activity would be transported to the active volume of the SNO detector by a gas-capillary transport system, using pure oxygen gas as both target and carrier. An initial investigation of production rates, transport times and general feasibility of this scheme has been carried out at the D-T generator facility in the Health Physics Department at AECL Research, Chalk River. Results of these tests are presented along with an optimization of the parameters required for a calibration facility for SNO.

I. INTRODUCTION

The nuclide ^{16}N β–decays with a 7.13 s half-life to the 6.13 MeV excited state of ^{16}O with a 68.8% branch and to the ground state of ^{16}O with $Q(\beta^-)$ = 10.42 MeV and a 26% branch. There is also a 4.7% decay branch which produces a 7.12 MeV γ-ray. Frati *et al.*[1] had proposed using the dominant 6.13 MeV γ-ray from this decay as a frequent ("everyday") calibration source for SNO. This proposal envisaged a D_2O recirculation loop semi-permanently installed in the acrylic vessel, and flowing past a medium intensity ($\approx 10^5$ n/s) D-T generator (located in the control or utility corridor in the underground laboratory). The D_2O would be used to transport the ^{16}N activity produced via the $^{16}O(n,p)$ reaction.

The D_2O water circulation scheme has the advantages of being fairly conventional in conception, and requiring a modest neutron flux. However because of the rigid purity and security requirements of the working fluid (D_2O), such a system would need a substantial engineering effort and capital outlay. The water system would also be limited to delivering only ^{16}N because of its chemical composition and slow transport time.

We therefore propose using a D–T neutron generator with either gas, liquid or solid targets to produce different activities for calibrating the SNO detector. The activities produced would be conveyed to an appropriate volume or "decay chamber" inside the acrylic vessel by fast (of the order of 1 s) transport using gas flow through a Teflon capillary tube. Gas-capillary transport systems have been utilized since the early '70's to study short-lived activities at various accelerator laboratories[2]. Pioneering work in collecting and transporting recoil atoms by a gas-capillary system with aerosols was done by a group at the University of British Columbia using a D–T generator for 14 MeV neutrons[3]. Members and collaborators of the ISOL group in the TASCC facility at CRL use a He gas-capillary transport system with a NaCl aerosol on a routine basis. Collection and transport of short-lived activities via gas transport systems is a mature technology.

II. PROPOSED SOURCES

The following activities which can be made and transported by a D–T generator and gas-capillary transport system have been identified to date as useful calibration sources for SNO :

1. ^{16}N – There are several methods of producing and transporting this activity:

   a.) $^{16}O(n,p)^{16}N$ {Q = –9.64 MeV} with the target in the form of a reservoir of H_2O or D_2O surrounding the neutron production source. The ^{16}N could then be swept out by the transport gas stream (probably N_2 gas). Because of the high target density, this method would undoubtedly give the highest production rate of ^{16}N and hence the lowest neutron intensity for a required count-rate in SNO. The technical problems are likely to be the high flow rate of gas required to sweep the water target with high efficiency, and the (resultant) water entrainment in the gas-stream followed by water

deposition in the capillary and decay chamber. Because of these potential problems, this method has not been experimentally studied.

b.) $^{16}O(n,p)^{16}N$ using pure O_2 gas as both target and transport gas. It is presumed that the ^{16}N ions from the reaction recombine with oxygen with the resultant NO or NO_2 molecules being transported. An experimental verification of this hypothesis has been carried out and is reported.

c.) $^{19}F(n,\alpha)^{16}N$ {Q = −1.52 MeV} with a Teflon (CF_2 polymer) target. The ^{16}N ions produced within approximately 1.2 mg cm^{-2} of the surface recoil out of the target and can be collected by the transport gas stream. The production rate of ^{16}N is too low to compete against methods (a) and (b). It has been experimentally verified however to demonstrate the feasibility of the recoil ion collection method. The experiment is reported below.

2. ^{8}Li : This nucleus β^- decays with an end-point energy of ≈ 13 MeV and $t_{1/2}$ = 0.838 s. It is an important source for a differential energy calibration in SNO since the β^- decay spectrum is very similar to the ^{8}B decay ν spectrum from the sun. This source will provide a spectrum shape for direct comparison when looking for (e.g. MSW) energy dependent ν_e flux suppression. It could be made by $^{11}B(n,\alpha)^{8}Li$ with transport of the recoils via gas + aerosol (say He + NaCl). The concept and production rates have been experimentally verified and will be reported in a subsequent document[4].

3. ^{17}N: (Proposed by E. Norman[5].) This nucleus decays with $t_{1/2}$ = 4.17 s via β^- (end-point ≈ 2.7 − 4 MeV) delayed neutron emission with a branch ≥ 95%. Since the β^- can be detected by Cerenkov radiation, this will provide a tagged source of neutrons for absolute efficiency calibration of the neutral current detection scheme in SNO. It can also be used for verifying the efficiency of the β–n coincidence method of ^{212}Pb detection proposed by E. Bonvin[6]. In principle this nuclide can be produced and transported in the same fashion as ^{16}N i.e. via $^{17}O(n,p)$ with a $^{17}O_2$ gas transport system. Because of the expense of separated $^{17}O_2$ gas however, it might be more expedient to have a ^{17}O metal oxide target, and transport the recoils with a N_2 gas stream.

In addition to these sources, virtually any nuclide can be produced and transported by this system if it satisfies the following criteria :

i Half-life ≥ approx. 1 second.

ii Must be produced by a neutron induced reaction.

iii If the target is solid, then the exit channel of the reaction must have a heavy particle, i.e. the reaction must be (n,p) or (n,α) to allow recoils to come out of the target material into the transport gas volume.

Ref. 3 lists many such nuclides that have been observed in a gas-transport + D–T generator system. The final requirement therefore is that the nuclide should be useful as a calibration source in SNO.

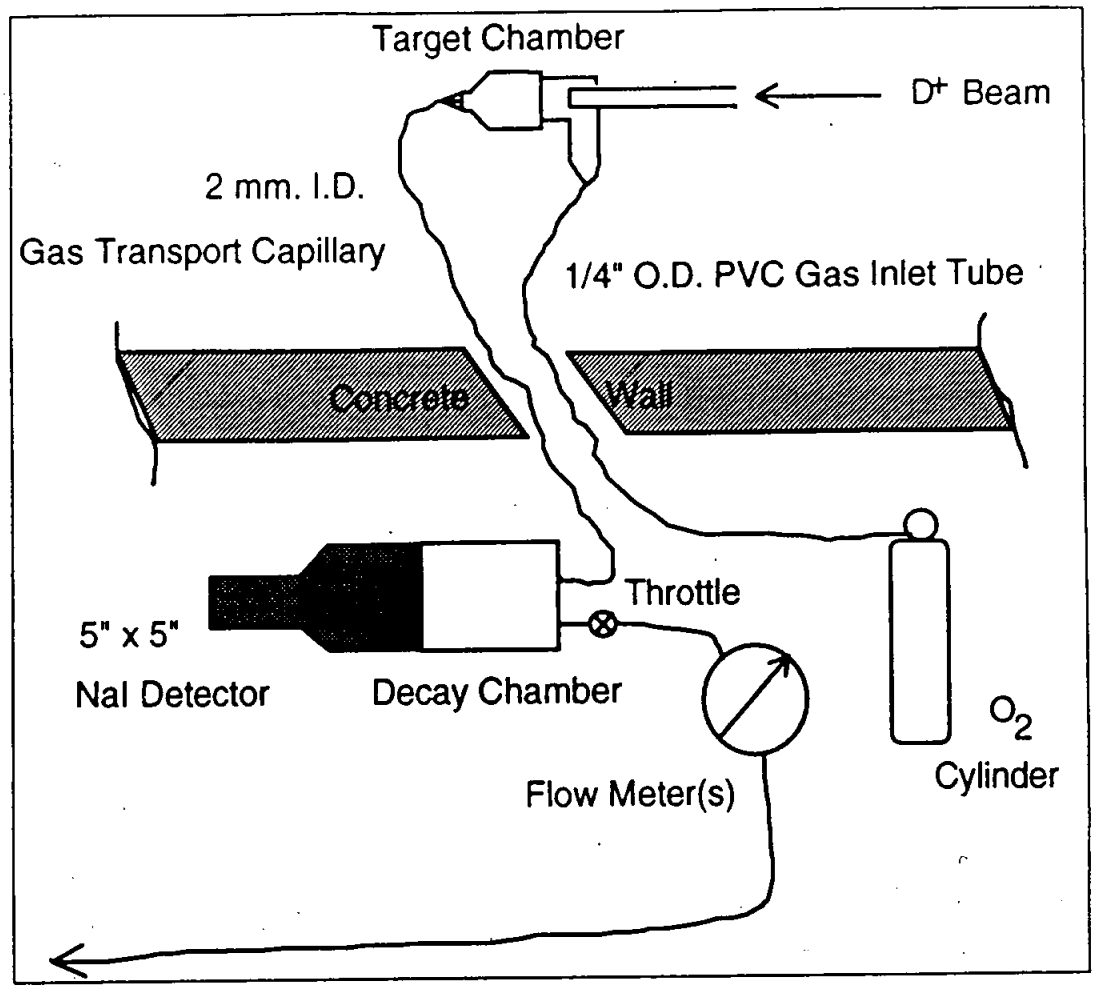

Figure 1: Schematic of $^{16}O(n,p)^{16}N$ Experimental Test Setup

III. DETAILS OF THE $^{16}O(n,p)^{16}N$ EXPERIMENT

An experiment was carried out at the D–T generator facility in the Health Physics Department at Chalk River Labs. to test the concept of ^{16}N production and transport in a stream of pure O_2 gas. The experimental set-up is shown schematically in figure 1. The neutron generator is a Texas Nuclear machine which generates up to a 1.5 mA d^{1+} (or p^{1+}) beam in a RF discharge source. The source can be biased up to + 150 KV. The beam is focused on to a water cooled TiT_2 (or TiD_2) neutron source at the end of a $\approx$ 4 m long beam tube. The accelerator and source are located inside a room with thick concrete walls for shielding. The ^{16}N target chamber was located next to the water-cooled neutron production source inside this room. The gas bottle(s), decay chamber, electronics etc. were located in the control panel area outside the concrete shielding. Gas transport lines were strung through a cable conduit in the concrete wall. A 1/4" O.D. PVC tube carried O_2 gas from a cylinder to the target chamber. The pressure at the cylinder could be measured and varied by a diaphragm type regulator.

The target chamber was cylindrical in shape (96 mm. diameter; 155 mm. long) with a 45° half-angle nose cone to promote laminar gas flow. The gas inlet was via a Bourdon type pressure gauge into three 1/4" Polyflow inlets. For all the gas flow rates scanned, there was no discernible pressure drop between the cylinder and the target chamber inlet. There were two gas diffuser plates made of electronic breadboards (plastic sheets with lots of holes in them) inside the cylindrical part of the target chamber to promote complete mixing of the gas. The target chamber was connected to the capillary tube at the end of the nose cone by a NW40 flange. This flange had seven short SS capillaries welded into it. The other end of these SS capillaries were all welded into a single short piece of 1/4" O.D. SS tube. Finally the connection to the Teflon capillary tube (0.095" I.D., 0.012" wall; obtained from Alpha via Electrosonics) was made through a "Cajon Ultratorr" 1/4" to 1/8" quick-connect type union.

The capillary transport tube was approximately 16 meters long. Outside the shielding, it was coupled into a decay chamber via a Cajon quick-connect and a gas diffuser plate. The decay chamber was cylindrical with 1210 mm. I.D. and 1560 mm. length (an old 5" × 6" NaI can). The gas outlet from the decay chamber was through a throttle valve which could regulate the gas flow, hence also the pressure inside the decay chamber. The outlet line was 1/4" O.D. PVC vented outdoors. The decay chamber pressure was monitored by a Bourdon type gauge, and the system gas flow rate was measured by two rotameters mounted in parallel on the decay chamber outlet (hence operating near atmospheric pressure).

γ-ray activity in the decay chamber was counted on-line by a 5" × 5" NaI detector placed end-to-end with it. The NaI detector had standard electronics. The NaI spectra were accumulated by a CANBERRA 35PLUS PHA, which could be downloaded into a PC. The neutron beam flux was monitored by a plastic-scintillator counter in a fixed location near the TiT_2 target. The efficiency of this counter for 14 MeV neutrons had been previously determined and was re-confirmed during the course of our experiments by cross-referencing it to ^{56}Fe activation foil analysis[7]. The calibration thus obtained was claimed to be accurate to 4% (mainly from the uncertainty in the Fe fast neutron cross-section). Thus the total neutron dose for each run was obtained by scaling the integrated counts from the plastic counter. The experiment was conducted with typical neutron fluxes of $\approx 5 \times 10^8$ sec^{-1} into 4π, obtained with a D^{1+} beam of about 100 μA at 150 KV. The tritium target was observed to deteriorate (desorb tritium) with a half-dose of about 1 mA-hour.

IV. EXPERIMENTAL RESULTS AND ANALYSIS of $^{16}O(n,p)^{16}N$

The experiment was run several times over the course of a two day period with different live-time, pressure, flow etc. settings and neutron fluxes. The NaI spectrum from one such run is shown in figure 2(b). The background spectrum taken with the neutron generator turned off is shown in figure 2(a). The room-background lines from ^{40}K(1460 keV) and ^{212}Bi(2614 keV; ^{232}Th decay chain) are prominent because the large, unshielded NaI detector was in close proximity to the concrete n-shielding wall.

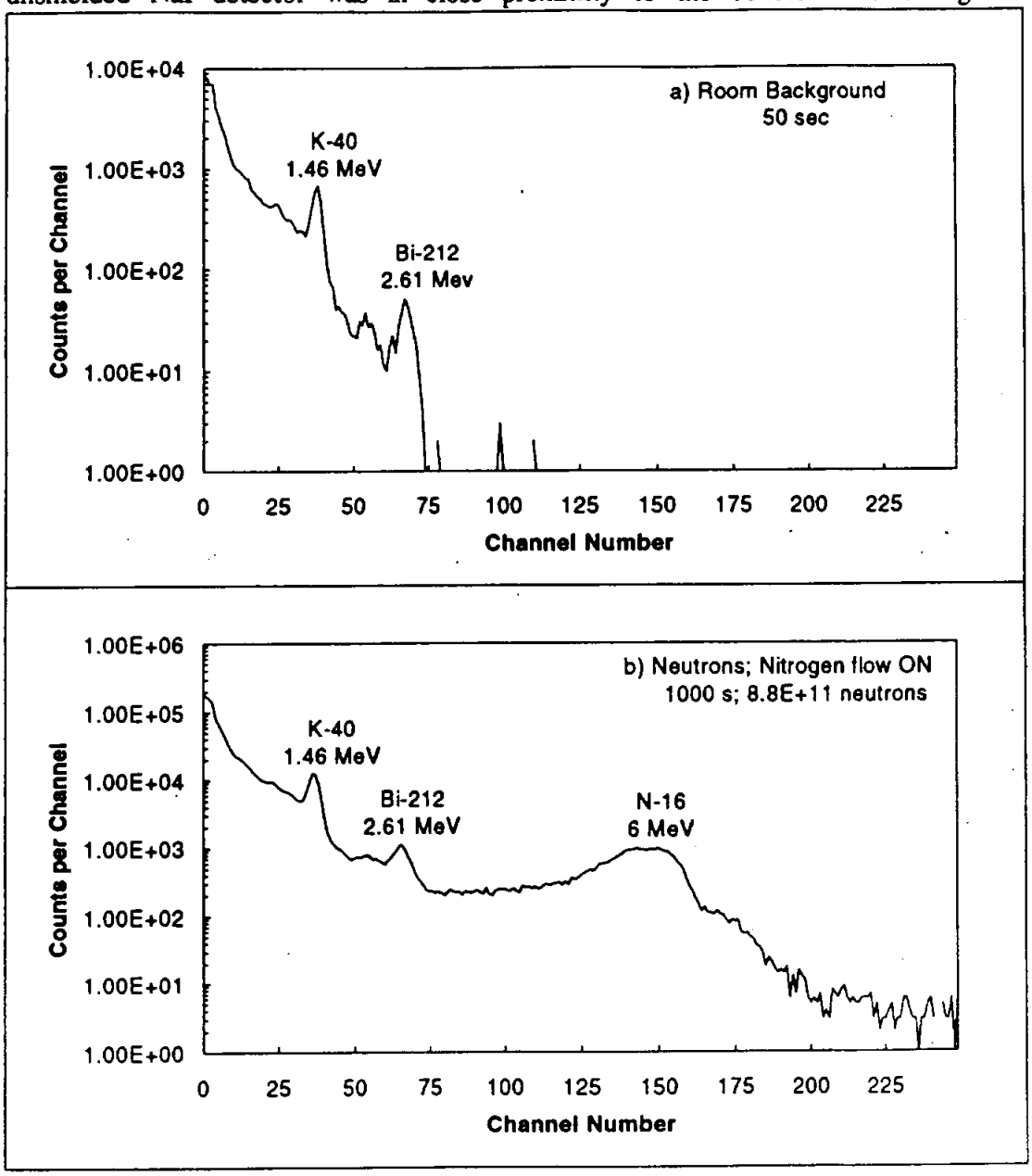

Figure 2: Data from the ^{16}O experiment

The 6 MeV γ–ray signal from ^{16}N in the decay chamber is unmistakable. The escape peaks and Compton edge cannot be separated from the full-energy peak because of the intrinsically "poor" resolution of NaI detectors.

Not shown in this figure is a background component which arises from prompt neutron capture γ-rays produced in the surrounding materials when the neutron generator is turned on. This component has a flat spectral shape that extends out to about 9 MeV (figure 5(b)). The integrated counts in the 6 MeV peak can thus still be extracted by subtracting counts due to a (assumed) flat background under that peak. The peak fitting algorithm in the CANBERRA analyzer was used to obtain this background subtracted peak area. To be conservative, a similar area was extracted using the same channel limits from the background (no neutron beam) spectrum. This area was then subtracted from the net foreground area and the errors were added in quadrature.

For the run displayed in figure 2 for instance, the 6 MeV peak yields 19236 ± 140 counts in a 1000 second run with a total neutron fluence of 8.7×10^{11} neutrons into 4π steradians (assumed isotropic). The target geometrically intercepted 30.8% of these neutrons. This was for a target gas pressure of 3 atm.(absolute), a decay chamber pressure of 2.47 atm., and a gas flow rate of 0.165 standard atm–liters per second. One now has to calculate the expected yield under these conditions. This is done in the following way:

First, the ^{16}N production rate per incident neutron in the target chamber is calculated.

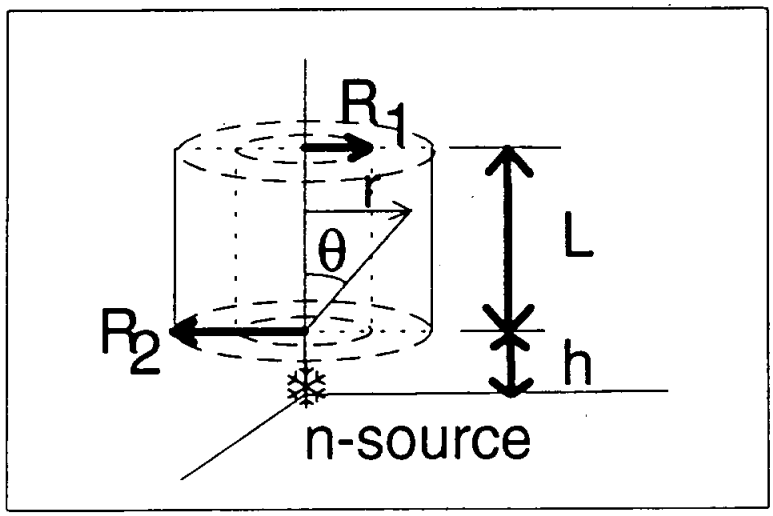

Figure 3. Generalized Geometry for Yield Calculation

The geometry for the generalized cylindrical annular target volume is shown in figure 3. It can be shown that in a volume element at (r,θ), the yield per neutron emitted isotropically into 4π is:

$$dY_n(4\pi) = \frac{\sigma\rho}{2} d\theta dr \tag{1}$$

where σ is the cross-section and ρ the gas density. The integration to find the total yield per neutron may be carried out in any order; doing the r integration first is more cumbersome, but more tractable and gives for the yield:

$$Y_n(4\pi) = \frac{\sigma\rho}{2}\left[\int_{\tan^{-1}\left(\frac{R_1}{L+h}\right)}^{\tan^{-1}\left(\frac{R_2}{L+h}\right)} (\{L+h\}\tan\theta - R_1)d\theta + \int_{\tan^{-1}\left(\frac{R_2}{L+h}\right)}^{\tan^{-1}\left(\frac{R_2}{h}\right)} (R_2 - h\tan\theta)d\theta\right] \tag{2}$$

which is easily evaluated, given that:

$$\int \tan\theta \, d\theta = \frac{1}{2} \log\,(1+\tan^2\theta) \tag{3}$$

In our case, for 14 MeV neutrons on ^{16}O, $\sigma(n,p)$ = 35 mb[8]. From the target chamber pressure of 3 atm. absolute, we can deduce $\rho = 1.61 \times 10^{20}$ atoms cm^{-3}; $R_1 = 0$; R_2 = 4.8 cm ; L = 15.5 cm and h = 2 cm. This gives the calculated yield per neutron emitted isotropically, $Y_n(4\pi) = 8.49 \times 10^{-6}$. However, the target intercepts only [1-cos(arctan(R_2/h)] of 2π steradians. Thus the calculated Yield per neutron *hitting the target* is:

$$Y = 2.76 \times 10^{-5} \ ^{16}N \text{ atoms per neutron} \tag{4}$$

To get from this fundamental calculation to how many counts one expects in the NaI detector requires estimating four efficiency factors. The first three are "transmission factors" corresponding to the fraction of ^{16}N atoms which (i) are delivered out of the target chamber, (ii) survive the transportation to the decay chamber, and (iii) decay in the decay chamber before being swept out by the gas stream. The fourth factor is the detection efficiency of the NaI detector for 6 MeV γ-rays emitted in the extended decay chamber geometry.

First, even though the Yield of eq.(4) multiplied by the neutron flux would give the production rate of ^{16}N, some of the product is lost because of the finite time taken to sweep out the target volume. It can be shown that if the turnover time of the gas in the target volume is τ_d, assuming complete mixing of the gas in this volume, the fraction of the total product delivered out of the chamber volume is:

$$\varepsilon_d = \frac{1}{1 + \frac{\tau_d}{\tau_{16N}}} \tag{5}$$

where τ_{16N} = 10.28 s is the lifetime of the product nucleus. In our case, for a chamber pressure, P_{tgt} = 3 atm., gas flow rate Q = 165 $cm^3\ s^{-1}$, and chamber volume V = 1100 cm^3, the turnover time,

$$\tau_d = \frac{V \cdot P_{tgt}}{Q} = 20.0\,\text{sec} \tag{6}$$

which in turn gives:

$$\varepsilon_d = 33\% \tag{7}$$

Next, some of the ^{16}N is "lost" due to radioactive decay during time spent in the gas-capillary transport line. The time taken by the gas to traverse this line, t_{trans} is calculated by integrating the time along the longitudinal dimension, x of the tube:

$$t_{trans} = \int_0^l \frac{P(x)}{Q} A\,dx \tag{8}$$

where P(x) is the gas pressure at point x along the length of the transport tube, whose total length is l. For laminar flow (according to Poiseuille's Law), the pressure drop in a tube of uniform cross-section, hence the time taken is a complicated but calculable function. However, here the flow must be turbulent since the Reynold's number $R_e \approx$ 6000. So we estimate the transit time by simply taking the gas pressure to be the average of the measured pressures at each end of the tube. Thus, in this case, P_{tgt} = 3 atm. and $P_{decay\ chamber}$ = 2.47 atm. For length, l = 16 m of the 2.41 mm diameter capillary, the transit time is thus t_{trans} = 1.2 sec. The fraction of ^{16}N that survives the journey,

$$\varepsilon_{trans} = \left(1 - \exp\left(-\frac{t_{trans}}{\tau_{16_N}}\right)\right) = 89\% \tag{9}$$

The third efficiency factor associated with the gas system is the fraction of ^{16}N decays observed by the detector due to the finite residence time of the ^{16}N in the decay chamber (assuming complete mixing). The decay chamber volume is 1800 cm^3 so the time spent by the gas in it, $t_{decay} = (V_{decay} \times P_{decay} / Q)$ = 27 sec. It can be shown that the fraction of ^{16}N nuclei which decay inside the chamber is:

$$\varepsilon_{decay} = \frac{1}{1 + \frac{\tau_{16_N}}{t_{decay}}} = 72.4\% \qquad (10)$$

So the fraction of the originally produced ^{16}N whose decays can be observed by the detector is:

$$\varepsilon_{tot} = \varepsilon_{del} \times \varepsilon_{trans} \times \varepsilon_{decay} = 21.3\% \qquad (11)$$

Finally, to obtain the number of 6-MeV peak events seen in the NaI detector, the branching ratio of the 6.13 MeV γ-ray and the detection efficiency in an extended geometry must be known. From the literature, for ^{16}N decay the 6.13 MeV branch is 68.8%. For the γ-ray detection efficiency the following two-step approach was adopted. A calibrated ^{60}Co source was used to determine the low-energy point-source efficiency. It was placed axially centered, 10 cm in front of the detector, and its γ-ray spectrum was recorded. The normalized room-background spectrum was subtracted and the total peak areas of the 1173 and 1332 keV lines (which could not be completely resolved) together with the peak area of the sum 2504 keV peak were extracted. Now the photo-peak efficiency at ≈1250 keV (<1173,1332>) can be estimated by the ratio of sum peak events to singles :

$$\varepsilon_{photo}(<1250>) = \frac{2 \times \varepsilon(1173) \times \varepsilon(1332)}{\varepsilon(1173) + \varepsilon(1332)} = \frac{2 \times N(2505_{\Sigma})}{N(1173) + N(1332)} = 1.78\% \qquad (12)$$

This efficiency could also be estimated from the absolute source strength calibration and was found to be 1.55%. The measured numbers were compared to two calculations. The efficiency tables of Marion and Young[9] gave an efficiency of 2.16% and an EGS4 Monte-Carlo simulation[10] gave 2.3%.

Thus with some confidence in calculations, the efficiency for 6 MeV γ-rays emitted uniformly over the extended geometry of the decay chamber (12.1 cm diameter and 15.6 cm height) was estimated again by two methods. The decay chamber volume was divided into 10 slices, and the total efficiency was calculated from the graphs of Marion and Young by assuming a point source at the center of each slice. The efficiency thus calculated was 1.5%. An EGS4 calculation was also performed[10] and the efficiencies for 6 MeV γ-ray components were found to be (a) ε(photopeak) = 1.17%, (b) ε(first escape) = 0.72% and (c) ε(second escape) = 0.06% for a total of 1.95% since these components were not resolved in the NaI spectrum. The average of these two methods was adopted:

$$\varepsilon_{peak}(6.13\,MeV) = 1.75\% \qquad (13)$$

The lower number was thought to be justified because the measured efficiencies at ~1.25 MeV were lower than the calculated values.

Now with all efficiencies in hand, the expected number of counts in the 6-MeV γ-ray peak could be calculated. For a total neutron fluence, ϕ_n of 2.68×10^{11} neutrons that hit the target volume, the expected number of counts in the peak is:

$$N_\gamma(\text{peak}) = \varphi_n \times Y \times \varepsilon_{\text{total}} \times \text{B.R.}(6.13) \times \varepsilon_{\text{peak}}(6.13) = 18969 \qquad (14)$$

for the run shown in figure 2(b).

The ratio of observed to expected is

$$\frac{N(\text{observed})}{N(\text{expected})} = 1.01 \pm 0.01(\text{stat}) \pm 0.25(\text{sys}) \qquad (15)$$

The statistical error is from the peak and background counts at 6 MeV. The systematic error is a conservative estimate assuming 5–10% errors in measurements (by eye-readings) of various pressures, lengths etc. needed to calculate the yield.

This result shows that:

a) The hypothesis of ^{16}N production and transport in a stream of pure O_2 gas is tenable and that therefore the postulated mechanism of ^{16}N transport is probably correct and close to 100% efficient.

b) Efficient transport takes place even for highly turbulent flow! In this case for instance, the Reynolds's Number was ≅ 6000.{ For laminar flow, the Reynolds no., a function of tube diameter, gas density, viscosity and velocity, should be less than 1000-2000.} This removes a considerable constraint on the design.

c) The method of calculating the yield is close to reality and can therefore be adopted and extended to design and optimize a "real" calibration source for SNO.

V. THE $^{19}F(n,\alpha)^{16}N$ EXPERIMENT.

The $^{19}F(n,\alpha)^{16}N$ experiment was carried out to (a) test the general feasibility of producing and transporting recoil ions made in a low-energy neutron beam and (b) test the yield calculations which were based on low-energy ranges for heavy ions. After initial tests done by inserting a roll of Teflon foil in the target chamber used for the ^{16}O experiment, the target chamber was changed to a much smaller volume while preserving almost the same solid angle coverage of the neutron source by the Teflon target foil. This greatly increased the overall yield (and therefore signal to noise) because of the increased delivery efficiency,ε_d [equation (5)]. The new target chamber geometry is depicted schematically in figure 4. The dimensions and materials of the rest of the gas-capillary transport and detection schemes were unchanged. The only other major change was a switch from O_2 to N_2 gas for obvious reasons. It was hypothesized that ^{16}N transport would take place in N_2 gas via similar chemical mechanisms as in O_2.

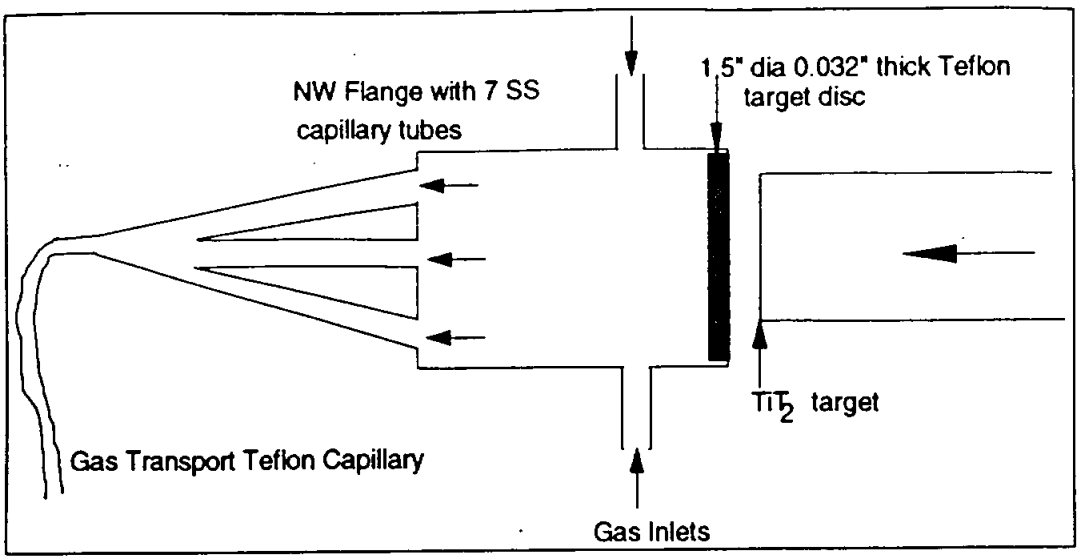

Figure 4: Schematic diagram of Teflon target set-up for recoil experiment.

VI. RESULTS AND ANALYSIS OF THE RECOIL EXPERIMENT

The experiment was carried out with gas pressures and flows almost identical to the previous experiment. The results of one series of runs are shown in figures 5. Figure 5(a) is the room background for a live time of 4000 seconds. The D-T neutron generator was not switched on while this spectrum was accumulated. For clarity, only the region from approximately 3 to 10 MeV is shown. The reader is referred to figure 2(a) for the full background spectrum. Figure 5(b) shows the "room background" when the D-T generator was turned on. For this data, there was no Teflon foil in the target chamber. There was virtually no difference in the spectra with and without gas flow. This shows that (i) most of the activity seen with the target in was indeed made by the target material (and not by other "inert" building materials) and (ii) that this background activity must be the result of neutron interactions in the material surrounding the detector. There have been hypotheses that the guilty party was either the thick neutron-shielding concrete wall or the iodine in the NaI detector itself. In any case, the shape of this neutron-induced background was flat up to ~ 9 MeV and thus does not interfere with the analysis of the 6 MeV line. Figure 5(c) is the NaI spectrum taken with the Teflon target installed and the gas transport system on line. Once again the 6 MeV γ-ray line from ^{16}N decay is unmistakable.

This γ-ray line, after room and neutron induced background subtraction, has 668 ± 30.2 counts for a neutron fluence of 1.61×10^{12} neutrons into 4π, i.e. a dose of 3.4×10^{11} neutrons on the target foil (assuming isotropic neutron emission). Once again the task is to compare this with the theoretical expectation.

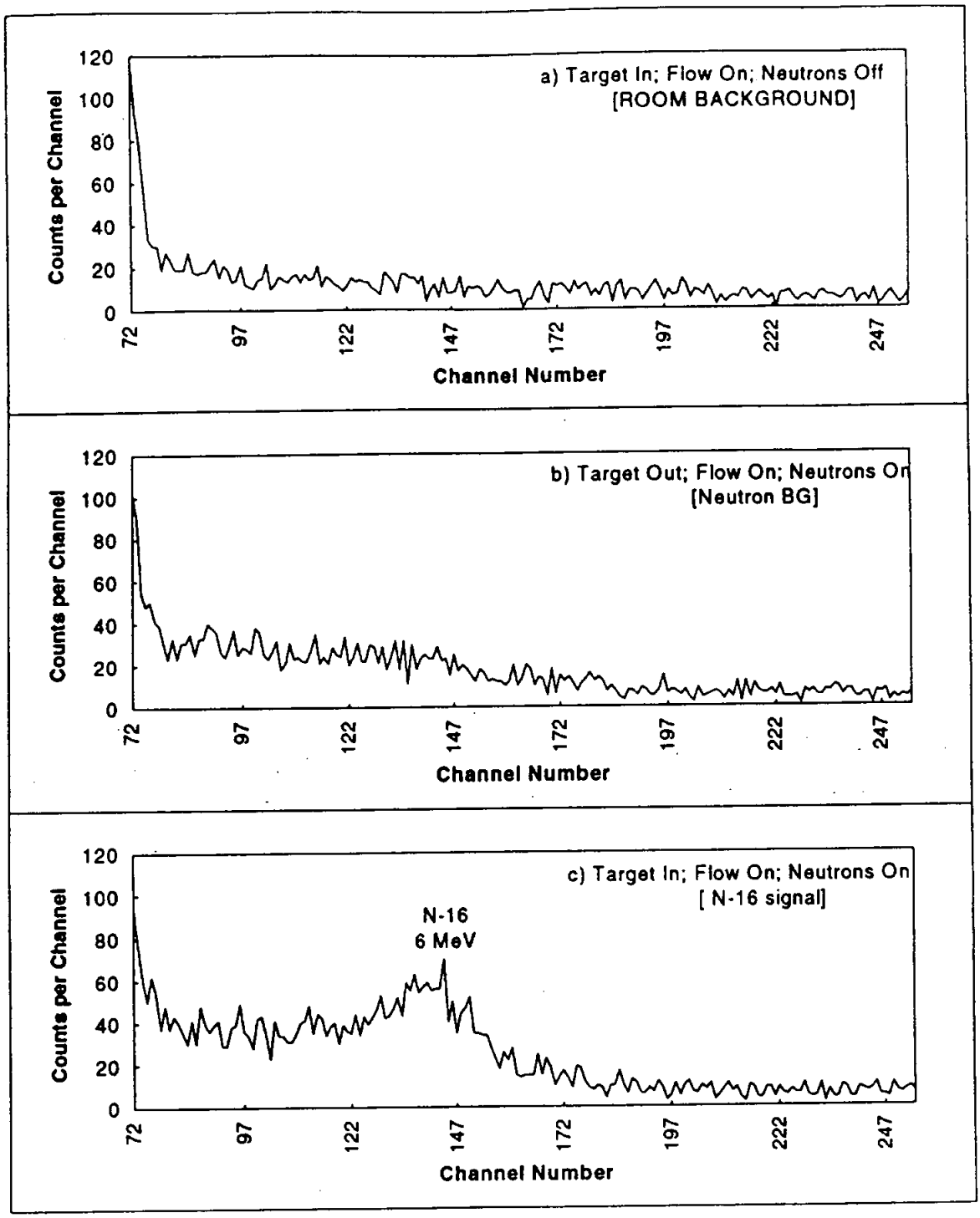

Figure 5: Data from the Teflon foil recoil experiment. (a) 4000 s room background run. (b) 2000 s, neutron background run with 1.6×10^{12} neutrons into 4π. (c) 2000 s, ^{16}N production run with 1.61×10^{12} neutrons into 4π.

For neutron induced reactions in a target foil, the products that escape the foil are those that are produced close enough to the surface so as to not "range out" in the bulk material. Assuming that the reaction cross-section, σ is isotropic in the center-of-mass (CM) frame and that neutrons are normally incident on the target foil, an analytical expression can be written for this yield Y_n:

$$Y_n = \int_{\cos\theta_{lab}=1}^{\cos\theta_{lab}=0} \frac{\sigma}{2}\frac{d\Omega_{CM}}{d\Omega_{lab}}(\theta_{lab}) \times \text{Range}\left[E_{recoil}(E_n, \theta_{lab})\right] \cos\theta_{lab}\, d(\cos\theta_{lab}) \qquad (16)$$

$d\Omega_{CM}/d\Omega_{lab}$ is the "boost" due to the forward coning of reaction products in the laboratory frame from isotropic emission in the CM frame. Range[...] is the range of the product ion in the target material for initial energy (velocity) determined by the kinetics of the reaction given the incident neutron energy, E_n and the emission angle of this product relative to the incident neutron direction, θ_{lab}.

This yield was calculated in two ways. A crude numerical integration in equation (16) was performed "by hand" by subdividing the interval into 4 bins and summing the weighted contributions from the evaluation of the integrand at the center of each bin. The Range[...] values were computed using the kinetics code "KINEQ" and the range code "STOPX" installed in the Nuclear Physics computer network at CRL. The cross-section was taken to be 25 mb[8]. This integration gave $Y_n = 2 \times 10^{-7}$ ^{16}N atoms per neutron. In addition, a Monte-Carlo evaluation was performed by Frati[11] for a normal incidence or "pencil beam" geometry as evaluated above and also for a point neutron source + flat disc target geometry as was the actual experimental situation. Ranges from the code "TRIM" were used. Frati has plotted the differential yield obtained as a function of the depth of the layer in which the reaction takes place, and it is instructive to note that in both cases the differential yield curve is almost a straight line which goes to zero at a target depth corresponding to the maximum recoil range ($\approx$ 1 mg cm^{-2}) of the product ions in the target material. The calculated yield in the forward direction only (corresponding to the experimental situation) is $Y_n = 1.97 \times 10^{-7}$ atoms per neutron.

With the new target chamber of 54 cm^3 volume, ε_d = 94%. Since the other parameters in this particular run were the same as the reported run in Section IV, the various efficiency factors were the same. Thus the calculated number of 6 MeV peak events in the NaI detector was 498 for a neutron fluence of 1.6×10^{12} neutrons in 4π. The comparison with experiment then is:

$$\frac{N_{observed}}{N_{expected}} = 1.34 \pm 0.07(\text{stat}) \pm 0.33(\text{sys}) \qquad (17)$$

This experiment showed that:

1) The concept of catching and transporting recoil ion products of neutron induced reactions is valid.

2) The yield from such a process is quantitative (i.e. the recovery efficiency is ≈ 100%), and the cross-section values and estimated recoil ranges are reasonable.

3) As expected, the Teflon foil - recoil method of ^{16}N production cannot compete with the pure oxygen gas flow method in terms of production rate.

VII. OPTIMIZATION FOR SNO.

In SNO, the 14-MeV neutrons will be provided by an "oil-well logging" type neutron generator (produced and marketed in North America by MF Corporation)[12]. Such generators are typically 1.75" in total outside diameter (including insulating sheathing) in order to fit inside a standard oil well bore. They typically generate neutrons isotropically at up to ~10^8 neutrons/sec and (anecdotally) have a lifetime of about 10^{10} total neutron-hours. Such a generator will be located in the "neutron pit" (also commonly known as the "Nitrogen-16 pit"), with a gas transport capillary running to the acrylic vessel. It is assumed that because of the cylindrical geometry of the neutron generator, the oxygen gas target chamber will be a cylindrical annulus surrounding the source.

The dimensions of such a target chamber are determined by maximizing the delivered yield of ^{16}N atoms per neutron. The dependence of the yield on the geometry and operating parameters (target chamber gas pressure and gas flow rate) are given by equations (1), (2), (3) and (5). A computer program has been developed which carries out the optimization of the geometry for maximum yield given the operating parameters. A set of computations have been carried out with the inner radius of the annular target chamber fixed at 2.5 cm. The results are shown graphically in figure 6.

Figure 6(a) shows the maximized yield at the target chamber outlet as a function of gas flow rate for different chamber pressures. As expected, the yield is a monotonically increasing function of both these quantities. The operating point will be determined primarily by engineering constraints, namely the strength of materials (chamber, gas flow lines) and how long the limited supply of gas underground will last. As a point of comparison, a liquid air (oxygen or nitrogen) self-pressurized storage dewar has a typical gas pressure of 225 psiG (16 atmospheres absolute). At a gas flow rate of 500 atm-cc/sec, a 50 liter liquid oxygen tank will last approximately 1 day, and a standard pressurized gas cylinder containing 8 cubic meters of NTP gas would last a little over 4 hours. In any case it is seen that the "desired" goal of 100 decays per second in the ^{16}N calibration source is easily reached with a neutron generator flux of $\leq 10^7$ neutrons per second. In this calculation, no account has been taken of the activity transport time over ~50–60 meters because of uncertainties due to the turbulent nature of this very large flow. However it has been shown by the experiments detailed earlier that the significance of this turbulent flow is not great. In any case, the activity lost during transport will be ≤ 10%.

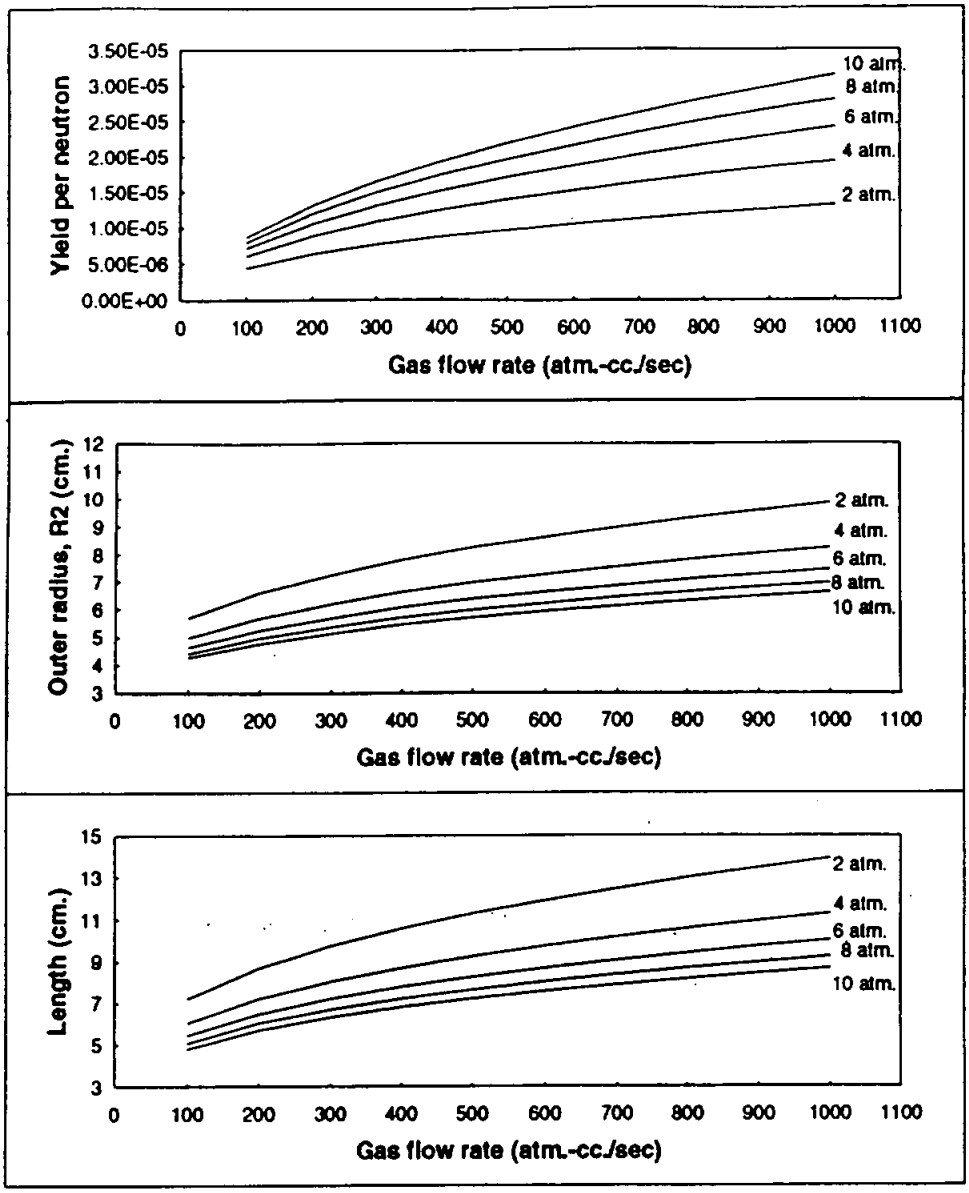

Figure 6. Optimized Yields and dimensions as a function of operating parameters. (a) Yield of ^{16}N delivered from target chamber. (b) Optimized outer radius of annular target chamber for 2.5 cm fixed inner radius. (c) Optimized Length.

Figures 6(b) and 6(c) show the optimized outer radius and length respectively of the annular target chamber (of fixed inner diameter, 5.0 cm.) for the same range of parameters as in figure 6(a). It is interesting to note that although the ^{16}N yield increases with increasing target chamber pressure and gas flow, the optimum dimensions of this chamber actually decrease.

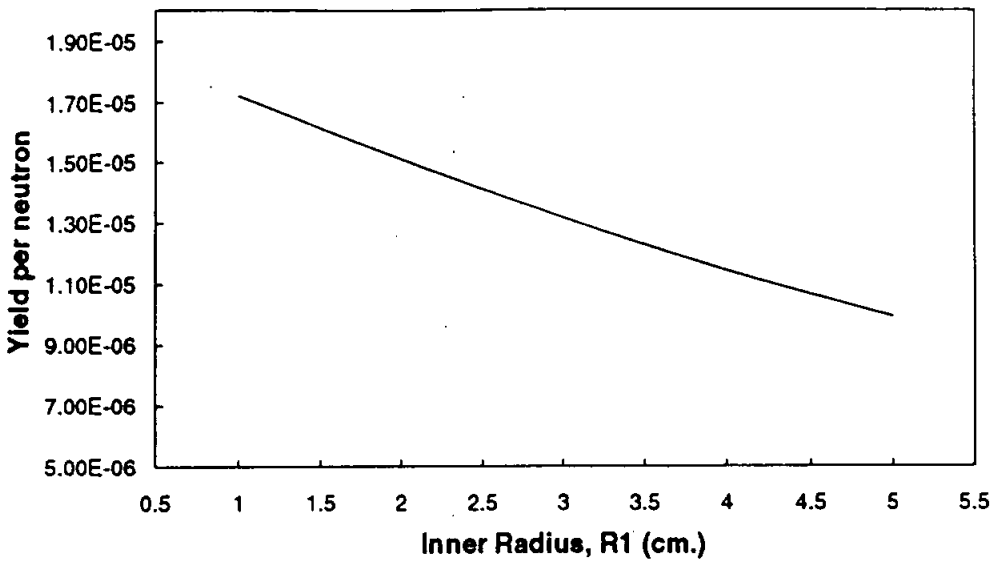

Figure 7. Optimized Yield vs. Inner Radius of target chamber for chamber pressure = 4 atm. and flow = 500 atm.-cc./sec.

Finally, using the computer code, we show that the yield increases as the inner radius is decreased. The optimized yield at the chamber outlet is plotted as a function of the inner radius in figure 7. For purposes of illustration, the target chamber pressure and flow rate have been assumed to be respectively 4 atm. (abs.) and 500 atm.-cc./sec for this calculation. Thus some gain in yield (i.e. an equivalent savings in neutron intensity and source life) may be obtained by using the target chamber itself as the H.V. insulating sheath around the generator in order to reduce the target chamber inner radius.

VIII. CONCLUSIONS

We have demonstrated the feasibility of making an intense, neutron-free, 6 MeV ^{16}N calibration source which can be semi-permanently installed and frequently used in SNO. This scheme will use a remotely located, moderately intense D-T neutron generator and a fast gas-capillary transport system with pure oxygen gas as both production target and carrier.

We have also demonstrated that it is possible to efficiently collect and transport recoiling products of neutron induced reactions in a solid target. This demonstration is particularly relevant for making a ^{8}Li calibration source (and possibly a ^{17}N source) for SNO. A direct demonstration of the ^{8}Li source is in progress and initial results are in good agreement with predictions[4].

A computer program has been developed for optimizing the parameters of the actual gas-calibration set-up in SNO. It is expected that the optimization code will evolve as the calibration system engineering design is developed.

The gas transport calibration system is a clean, relatively inexpensive and versatile addition to the operating features of the SNO detector.

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