Anode Wire Constraints for ^{3}He Proportional Counters in the Sudbury Neutrino Observatory

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Abstract

We present constraints governing the design of the anode wire for ^{3}He proportional counters used to measure the neutrino induced neutral current signal at the Sudbury Neutrino Observatory. Three factors which constrain the design are considered: mechanical forces, radioactivity, and electrical requirements. Copper is the only material considered for use as an anode wire because it meets all the basic requirements that are identified.

1 Introduction

We are designing a low background 3He proportional counter array for detecting neutrons released during the neutrino-induced, neutral-current dissociation of deuterium. An important design question is delineating the specifications of the anode wire from which the signal is obtained. In this report we consider three areas: mechanical forces, radioactivity, and electrical requirements which constrain the wire specifications.

The neutral current detectors as now envisioned will consist of individual counter elements 1, 2, and 3 m long. Detector strings up to 11 m in length are to be constructed from these individual counter segments. In the following sections we report our calculations for 50 μm diameter wire only, the most likely choice, and give lower and upper limits to the diameter based on the factors that are discussed.

2 Mechanical Factors

The wire must tolerate the stresses placed on it during tensioning, soldering, and detector cooling operations. It must withstand both gravitational and electrostatic forces. It must have good creep properties so that it will not sag with time, and it must withstand any dynamical loads during handling, shipment and installation. Table 1 lists the basic properties of copper along with some of the properties of nickel, from which the detector bodies are constructed. Nickel is included because it plays a role when considering effects due to thermal expansion.

Table 1: Properties of copper "101" (99.99 min. Cu, oxygen free) and Ni "270" (99.9 min. Ni)[1-3].

	Copper 10100: cold drawn	Ni 270 (99.9% Ni)
0.2% yield strength	380 MPascals	–
Modulus of elasticity	115 GPascals	207 GPascals
Coeff. of thermal exp.	17.0 μm / mK	13.3 μm / mK
Specific heat capacity	9.4×10^{-2} cal/gK	–
Melting point	1083 C	1454 C
Annealing temp.	375 - 650 C	350-550 C
Density	8.94 g/cm^3	8.88 g/cm^3
Electrical resistance	17 nΩ m	59.8 nΩ m

2a Type of copper

The first constraint imposed on the wire is a minimum mechanical strength. The intrinsic strength of copper or any metal is defined several different ways[4]. Since we want the wire to permanently deform as little as possible we have chosen the 0.2% Yield Strength as the appropriate measure of strength. This strength measures the stress necessary to cause a 0.2% permanent elongation of the wire. One actually wants to work below this number to stay within the elastic portion of the stress versus strain curve of the wire where short term deformations are largely reversible (see Fig. 1) and long term creep is more acceptable.
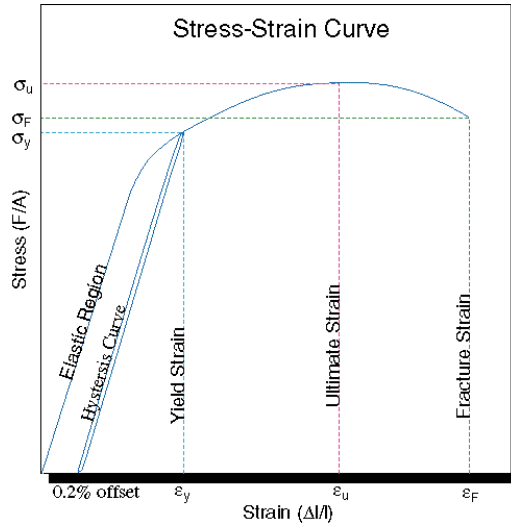
Fig. 1 Typical stress strain curve for a metal such as copper showing the various definitions of strength. The strain is change in length / rest length while stress is force / cross sectional area. Wire only tensioned to 0.2% yield strength will traverse the hysteresis curve after initial tensioning.

Only cold drawn copper (as opposed to annealed) where the copper has been worked at least 60% has sufficient strength for use as the wire. Annealed copper has a 0.2% yield strength that is no more than 80 MPascals (MPa) and is also very malleable thus creeping significantly with time. Cold drawn copper has a 0.2% yield strength of ~380 MPa as listed in table 1. In the calculations that follow we will limit the stress applied to the wire to less than 190 MPa giving us roughly a factor of 2 safety margin.

2b Stress calculations

The key mechanical stresses on the wire arise from five sources: 1) the stress induced in the wire from the cooling operation after soldering, 2) the cooling down of the detectors from room temperature, at which they are built, to the operating temperature of SNO, 3) the tension required in order to remove the catenary droop due to gravity, 4) the electrostatic forces generated by the wire being off center, and 5) any jarring during handling, shipment, and installation.

Item 1 requires calculating how much the wire heats up during soldering (assumed to take 10 seconds) prior to actually being fixed in place. A rough calculation yields an average temperature of 165 C extending 6 cm into the counter. (This calculation uses the basic equations for heat conduction and heat capacity of copper to estimate the amount of heating.) Cooling this section of wire to room temperature induces a stress of 16 MPa for a 1 m long anode wire. Item 2 is similar in that the wire is cooled from room temperature to 10 C. We have the fortuitous coincidence that the coefficient of thermal expansion for Ni is slightly smaller than for Cu. The nickel will contract slightly less thus keeping the wire under tension. The calculated stress for a 30 C temperature change is 13 MPa. Adding items 1 and 2 gives a total static stress of ~30 MPa which leaves 160 MPa as the maximum stress we can apply for tensioning the wire and still maintain a factor of 2 safety margin.

Item 3 determines how much tension we have to place on the wire if we are to test the counters horizontally prior to their insertion at SNO. The

concern is that displacement of the wire from the center of the detector causes a gain shift; in our case the gain shift is approximately 1% for a 0.08 cm position shift[5]. A significant catenary droop will introduce a position dependent gain shift. (Note that this droop is removed when the detectors are installed in SNO because of their vertical orientation and thus only affect the test phase.) Equation (11) from Ref. 6 gives the maximum deflection as a function of tension (T), mass (per unit length), and the length (L) of the wire between supports:

$$\mathrm{Defl} = \mathrm{mass} * g * \frac{L^2}{8T} \qquad\qquad \mathrm{Eq}\ (1)$$

Table 2 uses Eq. 1 to calculate the maximum deflection (column 2) of a 3 m long, 50 μm diameter copper wire as a function of applied tension (column 1, 190 MPa = 40 g). The third column shows the results of a simple tensioning experiment. Because only the relative deflection was measured using 30 g as the zero deflection reference, the data have been corrected in column 4 assuming that the theoretical calculation at 30 g is correct. The key conclusion is that at a tension of 160 MPa (33 g) the deflection initially will be less than 0.07 cm. (Actually the deflection will be even less than this number because of the cooling down after soldering.)

Table 2: Maximum deflection of 3 m, 50 μm wire at various tensions.

Tension (g)	Defl (cm)	Expt (cm)	Expt Corr (cm)
1	2.0	–	–
2	1.0	0.91 $\pm$ 0.03	0.98
3	0.68	0.64	0.71
5	0.41	0.36	0.43
10	0.20	0.16	0.23
20	0.10	0.079	0.15
30	0.068	0 by def.	0.068
50	0.041	–	–
100	0.020	–	–

Item 4 uses the average deflection due to gravity or any type of misalignment of the wire that displaces it from the center of the tube to calculate the additional deflection due to the resulting nonuniform electrostatic field. The expression to calculate this deflection is based on equation (1) where m*g is replaced by the force per unit length due to the nonuniform field[7]:

$$\text{Defl} = \left[\frac{2\pi\varepsilon_{o}V^{2}(\delta + \text{Defl}/2)}{R^{2}(\ln(R/r))^{2}} \right] \frac{L^{2}}{8T} \qquad \text{Eq (2)}$$

In this expression ε_{o} is the permittivity constant, δ is the initial average misalignment, V is the applied voltage, R is the radius of the counter, and r is the radius of the wire. Table 3 lists the additional deflection given the initial average off center position δ and an applied voltage of 2200 V. Clearly, this additional deflection is small compared to the initial displacement.

Table 3: Deflection of wire due to nonuniform electrostatic field.

Tension (g)	Defl (cm)
10	0.104 * δ
20	0.052 * δ
30	0.035 * δ

Item 5 takes into account any dynamical forces that might act on the wire from mishandling. For a 10 g acceleration, which is roughly what might be encountered if the counter were dropped directly onto a concrete floor, the stress on the wire is only 2.5 MPa assuming the counter is oriented vertically. For a horizontally oriented counter, the forces are more severe because of how the forces add vectorially. Because there also is a frequency dependence which complicates the analysis, we will do a field test to understand the problems of shipping the counters horizontally including development of a specialized packing container.

2c Creep

Creep occurs in almost any material when it is subjected to continuous loading. The wire will creep to some extent because of the nominal starting stress of 190 MPa. The rate of creep is logarithmically proportional to time. In our case it is slower because as the wire creeps the tension causing the creep will decrease. There is surprisingly little data on the creep of cold worked copper. The following are rough estimates based on the best available data[2].

At 190 MPa the wire will creep 3.3×10^{-4} m/m in 100 minutes or 0.1 cm / 100 minutes for a 3 meter long wire. The tension will be reduced by 40 MPa to 150 MPa. At this new tension the wire will creep 3.8×10^{-4} m/m in an additional 2 years or 0.11 cm. The tension will be reduced by an additional 44 MPa to 106 MPa. There exists no data beyond 2 years. The actual creep of the wire will be substantially less than this amount because the tension continuously drops as the wire creeps.

To further reduce the creep rate we can pre-creep the wire. If we load the wire to 190 MPa for 100 minutes and then solder it in place we can remove the initial large creep. The wire will creep 1.7×10^{-4} m/m in an additional 15 hours and the tension will be reduced by 20 MPa. Over the next two years the wire will creep an additional 3.3×10^{-4} m/m while reducing the tension to 130 MPa. Of course additional pre-creep or pre-creep at a higher initial tension will further reduce the long term creep.

The poor long term creep data necessitates that we experimentally measure the creep rate for the wire of interest, which we plan to start soon. However, our initial estimates indicate that creep is not a significant problem especially once the tubes are oriented vertically and the tension just has to overcome the electrostatic forces.

2d Wire Uniformity:

One last mechanical consideration is the uniformity of the wire diameter. Diameter changes in the wire will cause gain shifts in the detector. For the neutral current detector we calculate this gain shift to be approximately 5% for a 1% variation in wire diameter[5]. Just a 1% shift in gain will broaden the FWHM of the 764 keV neutron line from 4% to 5%. Of course the magnitude of this shift will depend on what fraction of the wire is at one diameter versus another diameter. For a 50 μm wire manufacturers give a tolerance of ±0.6 μm or about 1%. However, experimental measurements indicate a position dependent gain shift over a 3 m counter to be around 1% which implies that the wire uniformity is considerably better than 0.2%.

2e Summary:

A reasonable safety factor is 2 for the yield strength versus applied load. The above calculations apply to 50 μm diameter wire, the most likely

diameter that we will use. However the same analysis can be applied to a 25 µm diameter wire and for the most part gives the same results because the strength and weight of the wire both scale as the radius squared thus the applied tension can be reduced by a factor of 4. The only exception to this statement is the induced tension from the cooling down of the wire and tube which will lead to the same absolute stress. This latter factor limits the wire diameter to no less than 25 µm.

3 Radioactivity:

We have chosen copper C10100 as our baseline material in part because it is normally very clean. C10100 is 99.99% copper with limits in ppm for 17 other elements[1]. Recent work related to double beta decay experiments[8] has shown that C10100 has the following activity levels: <0.03 dpm/Kg ^{208}Tl (40 ppt), <0.05 dpm/Kg ^{214}Bi (200 ppt) and <0.5 dpm/Kg ^{40}K (30 ppt). Assuming secular equilibrium, 6 ejected alphas per ^{232}Th decay, 8 ejected alphas per ^{238}U decay, and a mass of 14.5 g copper (50 µm wire, 800 m long), we get a total alpha emission rate of 19 per day. This value is an upper limit because some alphas will be absorbed by the wire itself as the range is only ~12 microns for a 6 MeV alpha particle which is comparable to the radius of a 25 µm wire.

Now turning to the photodisintegration rate we get only 0.7 gammas / day (2.615 MeV gamma from Th chain) which translates to less than one neutron / year. This rate is negligible compared to other neutron backgrounds. There is also the question of cosmogenically induced activity[8]. The highest observed activity at equilibrium is ^{58}Co (0.05 dpm/Kg) from the (n, α)2n reaction on ^{63}Cu. For our mass of Cu this reaction gives only 0.7 disintegrations / day which is negligible compared to other backgrounds.

Another way to consider the above contamination levels is to compare them with those arising from the Ni. If we assume that: 1) one quarter of all alphas within 12 microns of the inner surface get out, 2) the contamination levels are 10 ppt Th, 10 ppt U [ref 9], and 3) there is 800 m of 2.54 cm radius tubing we get ~365 alphas / day or 19 times as many alphas from the Ni as from the Cu. For the photodisintegration rate the ratio is over 1000 which is higher because the entire 350 µm thickness of the counter tube wall contributes to the background.

Thus from a radioactivity stand point our calculations indicate that 50 µm diameter C10100 satisfies our requirements and contributes substantially less to the background than the Ni bodies; indeed the 50 µm diameter wire contributes a factor of 19 less alpha particles and 1000 less neutrons than the Ni. For this reason we deem C10100 as a suitable material for the anode wire with respect to radioactivity.

4 Electrical:

Many factors constrain the specifications of the anode wire when considering the electrical properties. In this section we will consider applied voltage and resistance. These two factors which lead to upper and lower constraints, respectively, on the diameter of the anode wire have important effects on both background signals and the signal to noise.

The applied voltage coupled with the diameter of the anode wire determines the overall gas gain of the detector. Our design goal is ~100 for the gas gain. With the present gas mixture of 80% He, 20% CF_4 at a total pressure of 2.5 atm, one needs an applied voltage of 1650 V for a 25 μm diameter wire and 2200 V for a 50 μm wire[5]. Measurements have shown that spurious pulses increase with increasing applied voltage. Thus minimizing this voltage is important for minimizing the background. The result for the wire is that a smaller diameter wire is favored.
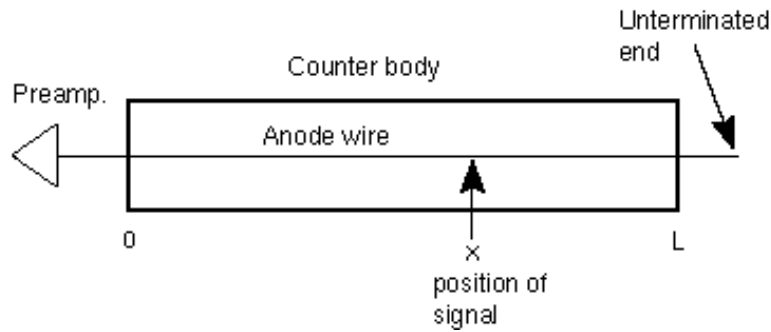

Fig. 2. Schematic of neutral current counter

The resistivity of the wire has a strong influence on the resulting amplitude of the signal pulses and thus the final signal to noise. Figure 2 shows a schematic of the anode wire connected to the preamplifier. Equation 3 is an expression for the time evolution of the output current pulse $i(t)$ at the preamplifier in terms of the input signal $i_o(t)$ and its position dependent attenuation[10]. Note that there are two components to the signal: the direct pulse and the pulse reflected from the unterminated end. The reflected pulse takes an additional time t_d to reach the preamplifier.

$$i(t) = \frac{A(x)}{2}i_o(t) + \frac{A(2l-x)}{2}i_o(t - t_d) \quad \text{Eq (3)}$$

The sum of these pulses is waveform digitized enabling the position of x to be determined from an analysis of the waveform.

The attenuation factor, $A(y)$, is an exponential function dependent on the position, y, and $\alpha(\nu)$ which is a frequency dependent factor owing to the resistive skin effect:

$$A(y) = e^{-\alpha(\nu)y}$$

$$\alpha(\nu) = \frac{1}{2}R(\nu)/\sqrt{L/C} \cdot \qquad \text{Eq (4)}$$
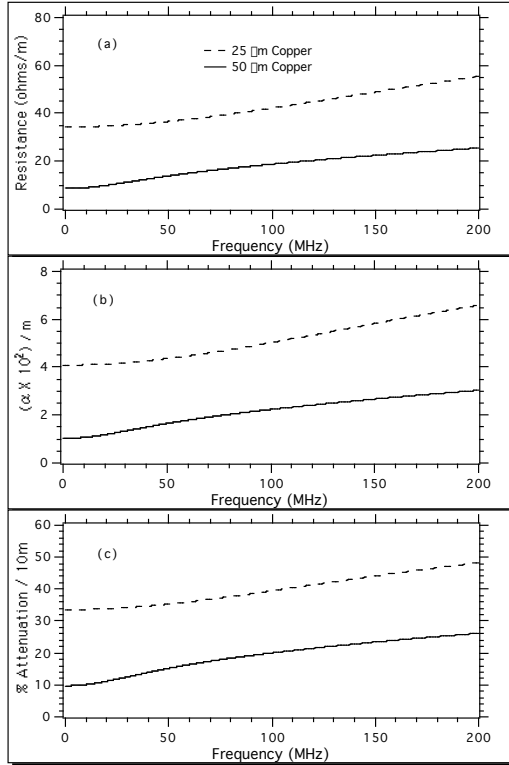

Fig. 3 Factors leading to attenuation of signal in 25 and 50 μm diameter anode wire as function of frequency. (a) shows resistance, (b) shows resulting $\alpha(\nu)$ factor in exponent of A(y), and (c) shows A(y) term itself[5].

At low frequencies, there is a roughly linear dependence of resistance with the cross section of the wire as is evident from the separation of the 25 μm and 50 μm curves in Fig. 3a. At higher frequencies the 25 μm wire degrades proportionally faster than the 50 μm wire. The resulting $\alpha(\nu)$ curves are drawn in Fig. 3b which closely follow the shape of the resistance curves because of the linear dependence. Finally, Fig. 3c shows the attenuation factors, A(y), for 25 and 50 μm diameter, 10 m long wires.

Consider the attenuation in a 10 m counter for 25 and 50 μm diameter wires. A reflected signal starting at the preamplifier end of the counter has to traverse 20 m before reaching the preamplifier. The signal in the 25 μm wire is attenuated just over 53% at low frequency while the signal in the 50 μm wire is attenuated only 18%. The higher frequency components are attenuated even more. Thus a larger diameter wire is favored in order to obtain the maximum signal to noise, and to minimize frequency dependence in the analysis of event-position.

Our conclusion upon considering pulse propogation effects is that the material from which the anode wire is made must have the lowest resistance possible and thus the wire should have as large a diameter as feasible. Copper is a good choice from this standpoint because only silver has a lower resistivity[11] (17.0 nΩ·m for Cu versus 16.0 nΩ·m for Ag). Consideration for spurious pulse rates associated with high-voltage discharge favors lower

operating voltages and thus a smaller anode wire diameter. A compromise towards a 50 µm diameter wire appears reasonable.

5 Conclusions

The strongest constraints on the specifications of the anode wire come from the electrical requirements. If copper is used, both mechanical and radioactivity considerations permit wire diameters ranging from a low of ~25 µm (mechanical constraint) to a high of ~250 µm (radioactivity constraint). The electrical requirements limit this range probably to 35 - 50$^+$ µm. A smaller wire attenuates the signal too much while a larger one requires too high an applied voltage leading to spurious pulses and an increased background.

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