Calibration of NEXT-100

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The goal is a full calibration of NEXT-100, most importantly in energy, but also spatial calibrations for necessary corrections for drift attenuation, light collection efficiencies, and instrumentation variations in HV, $\vec{E}$, and EL uniformity.

Current choice is $^{137}_{55}$Cs on central axis (Secs. 2.1 and 2.2), and $^{214}_{83}$Bi source (in equilibrium inside a $^{238}_{92}$U source) external to the outer Cu shield, but not shielded by the Pb Castle wall (for example, by temporarily replacing a Pb brick for calibration) (Sec. 4.1).

The rest of this note can be ignored as options that were considered but rejected for some reason. There may be a "missed gem" among them, but not likely.

Nuclear γ rays of known energy are the particle of choice for calibration, primarily because they must travel across the Xe volume [1] For γ's, their mean-free-paths in the Xe range from 1.5m to 3m and, therefore, to capture the entire energy of the initial γ requires repeated Compton scatters within the 1-meter sized Xe volume. The table in App. A has mean-free-paths for all calibration γ's.

It is useful to recognize that to be useful as a calibration γ, all of the Compton scatters must occur within the fiducial volume, be drifted to

*John Hill (nuclear) suggested $^{24}_{11}$Na and Jerry Lamsa (high energy) did the GEANT simulations for γ's penetrating the SS and Cu.

[1] α's and β's cannot do this, except for an internal conversion (IC) electron, but there are many atomic levels, there must be some decaying parent, and the electron energy is sometimes not precise.

the EL, and measured. If a Compton electron exits the drift volume before it stops or if after scattering the photon exits the volume, that γ is not useful for calibration.

It is best if the first Compton scatter is large angle with a large energy loss to the γ, since the mean-free-path decreases at lower energy and subsequent Compton scatters are spatially confined, but the mean-free-path is still about 1m at 500 keV. Because of the large mean-free-paths, most Compton signals will be spatially dispersed. For these reasons, lower energy γ sources ($^{137}_{55}$Cs) are better than higher energy sources.

However, the photo-electric (*pe*)process produces a single electron in one place in the Xe, although it will wander over a range from 5-20 cm. The *pe* process has a cross section that is 14% of the total at 662 keV and as large as 2% at 2500 keV. This seems the best scattering process for calibration and I will assume that the best useable calibration signal from a γ source is a *pe* electron. This may be pessimistic by a factor of two, since some fraction of the repeated Compton scatters will also be useful.

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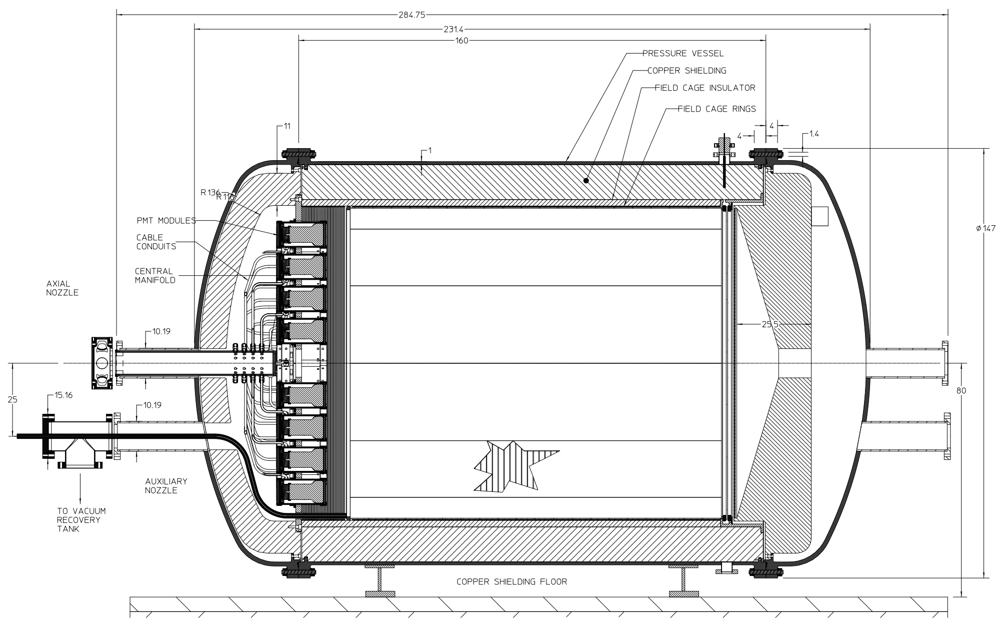

Figure 1: rz view of NEXT-100. (fig:rz)

1 Introduction

This is a draft of possible sources and particle delivery schemes for calibration of NEXT-100, shown in Fig. 1. We might want at least three sets of calibration data:

1. a whole-chamber volume illumination with a fixed-energy particle deposit to calibrate relative response across the EL grid in (x, y) and to map the PMT response for reflections from all directions;

2. a fixed-energy deposit at known z positions to calibrate drift velocity and attenuation; and,

3. a γ source directed along the z-axis at $r = 0$ as in the $^{137}_{55}$Cs source in the LBNL prototype. This will tell us the resolution we must achieve in the remainder of the chamber after fiducial, attenuation, and radial efficiency corrections are made.

The first (whole chamber illumination) can be achieved in three ways:

- by metering $^{41}_{18}$Ar gas into the Xe volume (Sec. 3). After equilibrium is reached, the two γ's from its decay will pepper the volume uniformly. Their mean-free-paths are larger than the chamber, and the response will have a (calculable) drop off near the edges for those Compton scattered γ's that leave the chamber. The $^{41}_{18}$Ar will decay away with $T_{1/2} \sim 2$ hours. The isotope $^{83}_{36}$Kr is used is ALEPH, STAR, and ALICE TPCs for calibration. It does not look promising to me (Sec. **??**).

- by shining 2447 keV γ's from $^{214}_{83}$Bi into the Xe volume for outside the chamber, and using the *pe* conversions. This is not as crazy as it might seem (Sec. 4.1)

- by positioning a point source on the z-axis just inside the PMT plane (Sec. 2.1

The second (fixed z energy deposits) can be achieved by shining a γ source into the chamber from the sides (along a fixed z) through 1-mm diameter collimator holes drilled in the 12-cm Cu shield (Sec. 2.3). A GEANT3 simulation has shown (Sec. 2.3.1) that the 1cm of stainless steel (SS) only cuts down the γ flux by a factor of two and, therefore, there is no need to position sources inside the pressure volume. Several sources at several z positions would be best for absolute spatial (*i.e.*, drift velocity) calibration and total energy calibration. These sources could be brought in from the sides through "source tubes" and positioned at the 1-mm openings in the Cu shield. Sources can be $^{137}_{55}$Cs , $^{60}_{27}$Co , $^{24}_{11}$Na , and $^{214}_{83}$Bi .

The third (a source along the axis, inside the Xe volume) can be achieved with a γ source that is brought in through the 'driver' port as shown in Fig. **??**, and is collimated by approximately a 20cm-long 1-mm diameter collimator hole in a Cu plug. Derek estimates there is space for this, and it must be fully retractible. Probably the $^{137}_{55}$Cs source is optimum, and it would provide a well-understood calibration on the $r = 0$ axis without corrections other than drift attenuation.

A fourth delivery mechanism is to shine thermal neutrons through a hole in the Cu shield to activate Xe isotopes within the Xe volume. There are many possible reactions, (n, γ), (n, α), and (n, p), but there are two problems: there may be *too many* reactions, and the neutrons will almost certainly radio-activate (at some small level) the heavy metals in the SS wall (up to 30% Chromium and Nickel). Nevertheless, an ideal would be the production of a nucleus by (n, γ) that would undergo internal conversion to fixed-energy electrons. The electron would always be there, and very localized, sometimes accompanied by the γ's Compton scatters. This has not been pursued.

2 Solid sources: ${}^{24}_{11}$Na, ${}^{60}_{27}$Co, ${}^{137}_{55}$Cs

The γ's from all these sources have mean-free-paths from 1.5m at 662 keV up to 3m for the higher energy γ's, and therefore they will illuminate the chamber almost uniformly (see App. A). The S_0 signal in NEXT will allow almost any source to be used, and this is a big advantage over other experiments, *e.g.*, the STAR TPC[1] that must use a random trigger in its calibration using ${}^{83}_{36}$Kr decays.

The source ${}^{24}_{11}$Na has short half-life of 15 hours and in order to use it we need a local reactor, like what you night find in a hospital. Why go to this much trouble? One reason is that ${}^{24}_{11}$Na has two very clean γ's that bracket Q= 2457 keV at which we need to calibrate. For precision energy calibration, this is pure gold. Furthermore, ${}^{24}_{11}$Na may just be the only such nucleus [3].

${}^{24}_{11}$Na $\rightarrow \gamma'$s at 1368 keV and 2754 keV

- This is the "only nucleus in the universe" that has two high-energy γ's with essentially no background decays, and the energies bracket $Q_{2\beta0\nu} = 2457.83$ keV.
- The mean-free-paths of both γ's (about 3m) are larger than the chamber size.
- Half-life is $T_{1/2} = 15$ hours; Activity $= 8.9 \times 10^6$ Ci/g. (1 Ci $= 37 \times 10^9$ Bq)
- Can shine through a Cu collimator hole at fixed z.
- Short half-life requires activation in a reactor. We should look for one in Zaragoza, where the drive to Canfranc is less than $T_{1/2}$ (no speeding). The production reaction is by thermal neutron capture,

$$ {}^{23}_{11}Na\ (n,\gamma)\ {}^{24}_{11}Na \qquad \sigma_\gamma \sim 0.5\text{b} $$

${}^{60}_{27}$Co $\rightarrow \gamma'$s at 1173 and 1333 keV

- Half-life is $T_{1/2} = 5.27$ y; Activity = 1130.36 Ci/g.
- Can shine through a Cu collimator hole at fixed z.
- Sum of γ energies is 1173.2 + 1332.5 = 2505.7 keV. This is just above the Q= 2457 keV, so too much ${}^{60}_{27}$Co with two γ's overlapping in space and an escape γ of 50 keV is background to $0\nu2\beta$.

Table 1: All γ's from ${}^{24}_{11}$Na . [3]

γ_{mode}	E(keV)	BR(%)
γ $(M_1 + E_2)$	996.78	0.0013
γ E_2	**1368.60**	100.0000
γ (E_2)	**2753.99**	99.9440
γ $(E_2 + 0.3\% M_1)$	2869.48	0.0002
γ $(E_2 + 0.4\% M_1)$	3866.13	0.051-
γ (E_2)	4237.90	0.0008

${}^{137}_{55}$Cs $\rightarrow \gamma$ at 662 keV

- The mean-free-path in 15-bar Xenon gas is $\lambda = 159$ cm and, therefore, it will illuminate the chamber nearly uniformly across its diameter and its length.
- Half-life is $T_{1/2} = 30$ y; Activity = 87.0 Ci/g.
- Very well understood for calibration in the NEXT prototypes.
- Can be shined through a Cu collimator hole at fixed z.
- can be positioned on the $r = 0$ axis at the PMT end to illuminate the whole chamber.
- the photo-electron rate is 13.8% of the total.

The main issue for all sources is how to illuminate the Xe fiducial volume, then to remove the source "to infinity".

A point source inside the Xe volume (for example ${}^{137}_{55}$Cs , Sec. 2.1) would illuminate the entire chamber. If this same source were to be retracted inside a 20-30 cm long collimator hole, it would also be a directional source along the axis of symmetry (Sec. 2.2).

Transverse directional sources (shining collimated γ rays along a line at constant z through the Xe volume, Sec. 2.3) can calibrate drift velocity, and axially directed γ beams can calibrate (x, y) at the EL plane. Both can be positioned either inside or outside the pressure vessel. Obviously, outside is safer.

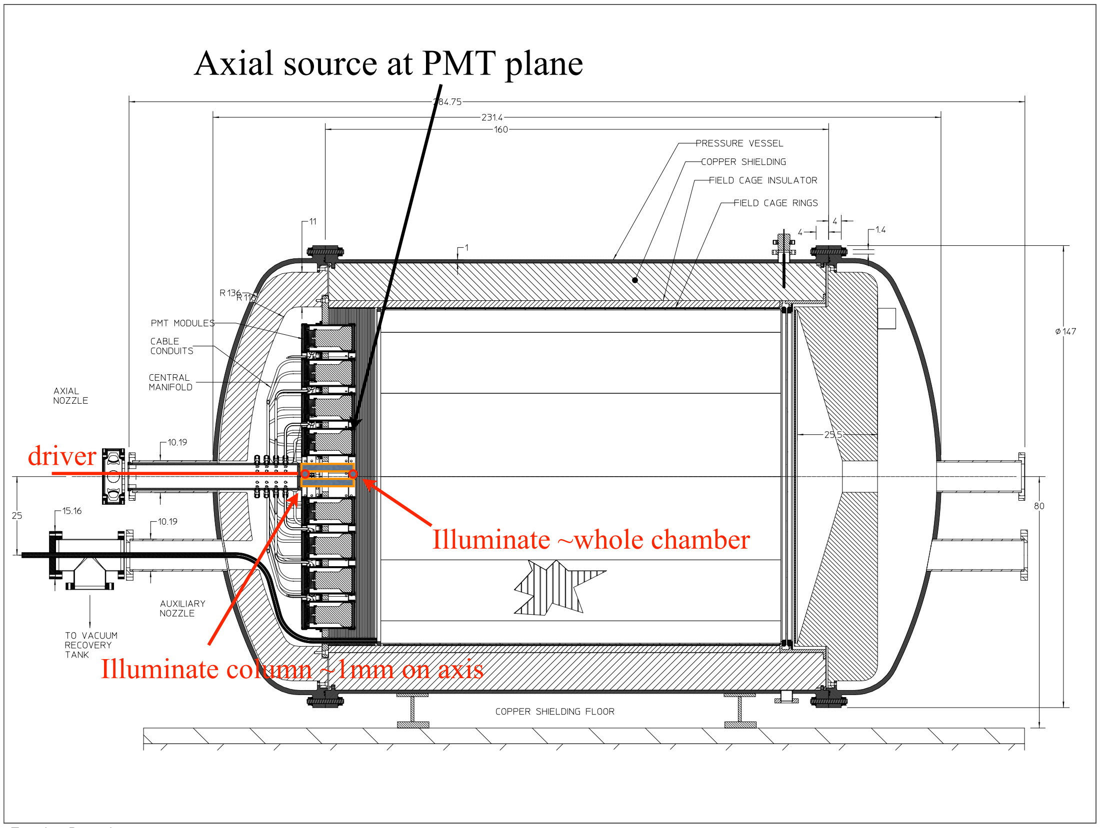

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Figure 2: A $^{137}_{55}$Cs or $^{60}_{27}$Co source on axis: forward position illuminates approximately the whole chamber; backward position is collimated by a 1-mm diameter hole in a Cu plug. (fig:rzs)

2.1 A point-source that illuminates the Xe volume

Positioning a source at the front edge of the PMT plane on the z-axis will illuminate the whole Xe volume, as shown in Fig. 2. This could be one of the solid sources ($^{60}_{27}$Co or $^{137}_{55}$Cs) and would be retractible through the driver access port. The volume illumination is not uniform, but $1/(r^2 + z^2)$ modified by drift attenuation along z.

The Compton electrons will bathe the HV plane and, probably, provide enough data for a “maximum drift time” estimate from which the drift velocity can be inferred. The drift velocity and the S_0 trigger will allow an estimate of z of each ionization from which the the attenuation can be estimated (with small corrections for the spatial non-uniformity).

This is a very good idea for a source position, especially since it can double as a source directed along-the-z-axis for a line illumination of the chamber, much like in the LBNL prototype, upon retraction of 20 cm into the Cu collimator. This is a particularly important calibration (it matches that done in the LBNL prototype) since it directly gives the optimum energy resolution possible without geometrical and radial corrections, varying EL efficiencies, or varying PMT efficiencies. Apart from attenuation, it is a direct, single (x, y) point calibration.

Use of a $^{214}_{83}$Bi source (really a $^{238}_{92}$U source that α, β decays down to $^{214}_{83}$Bi) would be very good here, but the $^{238}_{92}$U must be encapsulated *very safely.* Any small leakage will probably fatally contaminate everything and kill NEXT.

2.2 A source on the axis directed axially

The same source in the previous section can become an axially directed source by retracting it back through a Cu collimator, maybe 20-30 cm. The rate would decrease, but all γ conversions are on the axis and the only corrections are drift attenuation and variations of the light collection efficiency in z only, and both are smooth functions of z. This is exactly what was done in the LBNL prototype that achieved 1% FWHM.

2.3 Directional sources aimed across the chamber at fixed z

Derek has designed the Cu bars that make the 12-cm thick Cu shield in such a way that "fans" of 1-mm diameter holes can be drilled, all aiming back to a source position. There can be any number of holes drilled, from a single hole to 6-8 holes. Each acts as a γcollimator. Six of these fans around the circumference will illuminate planes at several fixed z positions, about 4-5 positions, from the EL plane to the PMT plane. The divergence of the beam would be about 1%, *i.e.*, 1-mm diameter hole over a depth of 12 cm, so the γbeam would be 1 cm wide at the opposite side of the chamber, see Fig. 3.

These fixed z γ's will calibrate the drift velocity and therefore the z coordinate in the chamber, in addition to providing direct measurements of attenuation. Since each 1-mm hole will illuminate a line, these data can also be used to calibrate deviations from perfectly axial ionization drift, *e.g.*, near the field cage and at the edges of the EL mesh.

These radial sources can be either outside the SS pressure vessel as in Fig. 3.

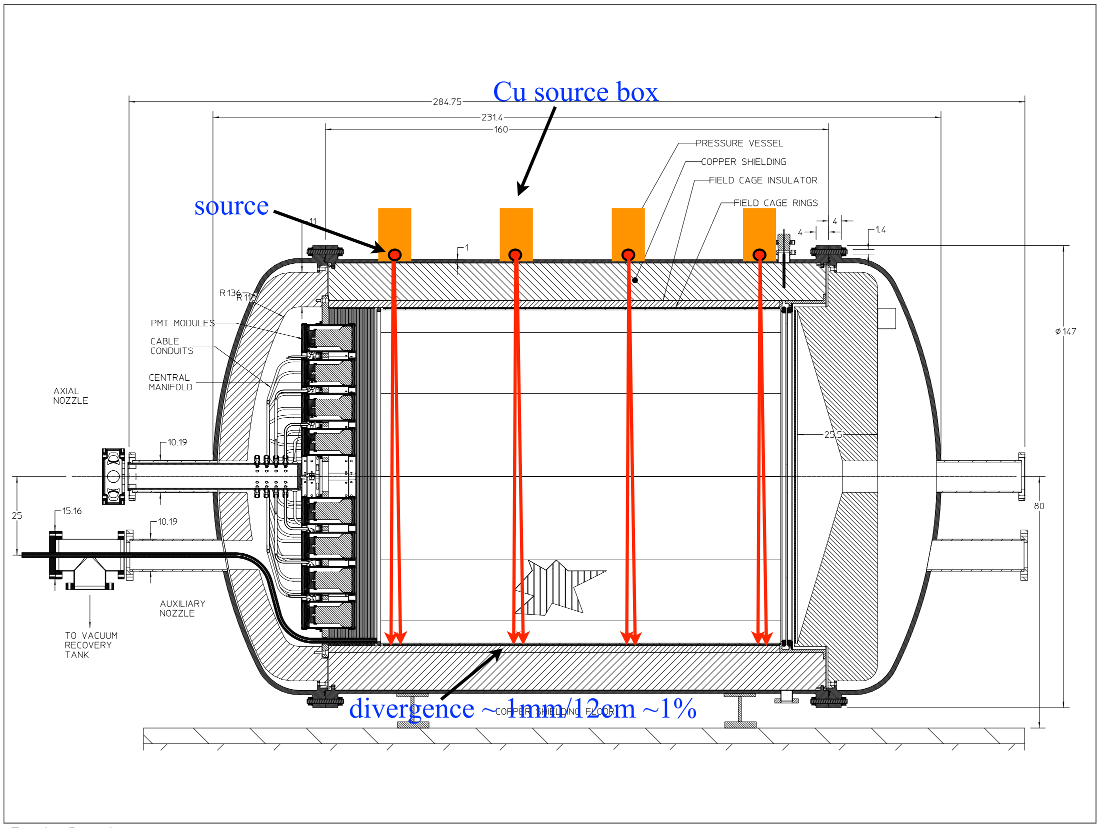

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Figure 3: Outside source, shining through 1-cm of SS and collimated by 1-mm diameter collimation hole in the 12-cm Cu shield. (fig:o-r-2-ss)

2.3.1 Sources that penetrate the SS pressure vessel

A $^{137}_{55}$Cs or $^{60}_{27}$Co source is positioned on the outside of the SS pressure vessel and aligned with the 1-mm diameter holes in the Cu shield. This position requires the γ to penetrate the SS vessel, from which there will be only a factor of two loss in intensity (App. A). See Fig. 4.

A GEANT3 simulation of $\sim 8 \times 10^6$ 662-keV γ's ($\sim$ 0.2 mCi) from a $^{137}_{55}$Cs source shined in from the outside of the SS pressure vessel (1cm of SS) and aimed at a 2-mm diameter hole in the 12-cm Cu shield. The sources was (1mm)^3. The energy distribution of all γ's emerging into the Xe is shown in Fig. 5 on the left, and the spatial distribution on the right. A 5-cm tungsten (W) pre-collimator (Fig. 6) improves the aim and reduces the clutter, but at a cost in rate, as seen in Fig. 7.

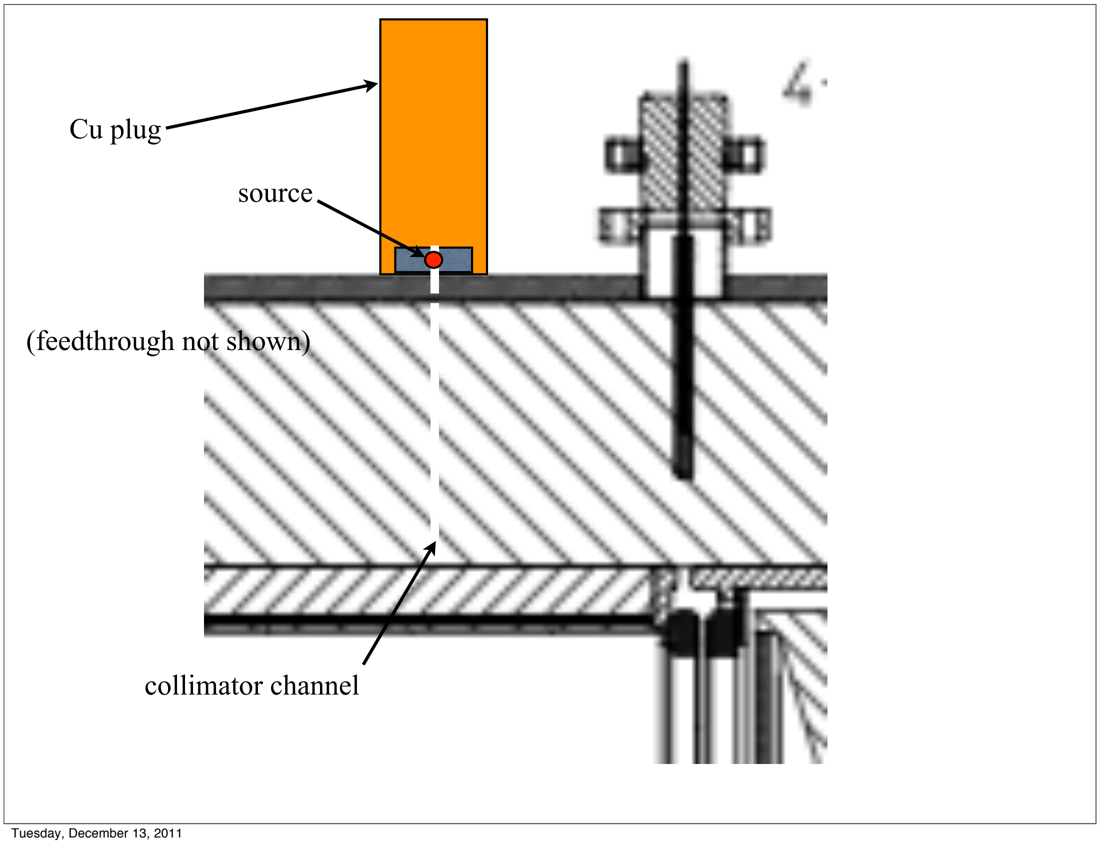

Figure 4: Close-up of 1-mm hole in Cu shield, Cu plug outside SS to close off any γ path into Xe volume, and source location (as set by a source tube). Also illustrated in this figure is the risky idea of reducing the depth of SS that a γ must penetrate by reinforcing around a drilled 1-mm hole in the SS vessel. (fig:o-r-2-ss-close)

2.3.2 Sources inside the SS pressure wall, but outside the Cu shield

The delivery of sources to the apex locations of the 1-mm drilled holes must be done by “source tubes” in grooves in the back of the Cu shield. These source tubes will snake their way around and through the Cu cap on the EL side, and out through an opening.

The sources must be “parked” somewhere safely far away from the Xe volume, certainly outside the Pb castle. This requires careful design work: do the sources stay within the Xe pressure volume, or do they penetrate the pressure volume and are parked farther outside?

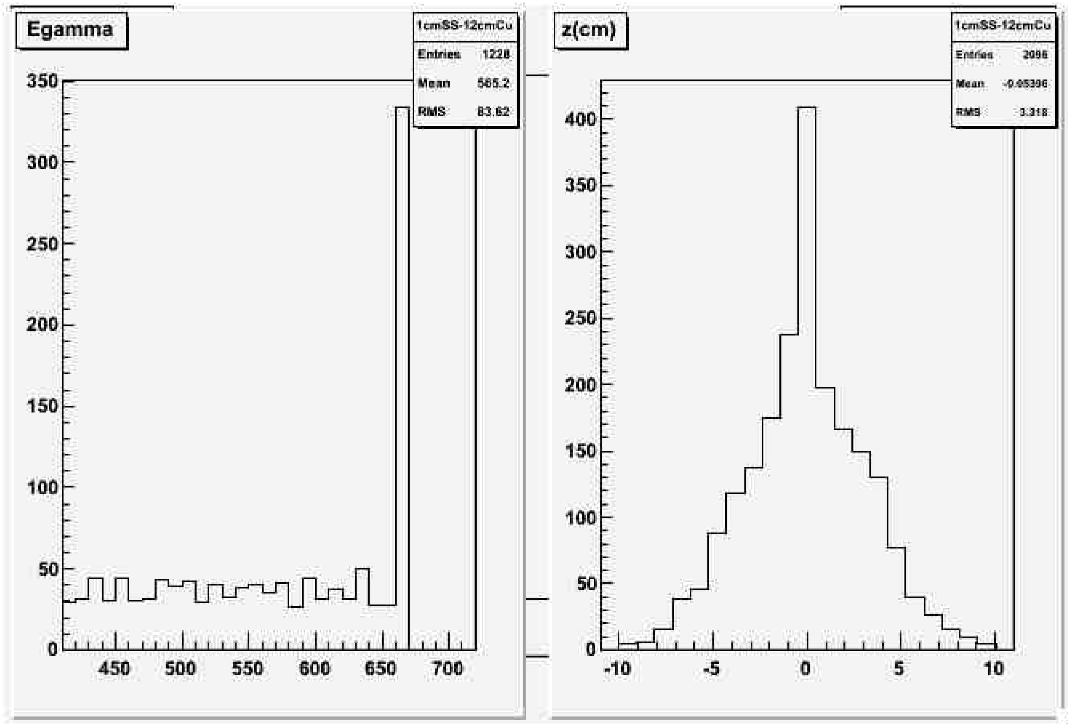

Figure 5: A $(1\text{mm})^3$ $^{137}_{55}$Cs source passing through the 1-cm thick SS and aimed at a 2-mm diameter hole in the 12-cm Cu shield: γ energy distribution (left), and γ z distribution along drift direction (right). (fig:SS-Cu)

One idea is Cuflon tubes fixed to the Cu shield on the outside. A wand with sources embedded in it at fixed distances corresponding to the positions of 1-mm collimator holes in the Cu shield. The wand is pushed through the Cuflon tube and is stopped at a precision point (so that all sources are aligned with all 1-mm holes). This wand will have to be coiled up outside the Pb castle. But should it stay inside the pressure volume, or penetrate the pressure wall an be parked outside?

Disadvantages There must be a lot of tubing, motors, and spools inside the pressurized Xe volume. Contaminations, leaks, failures, ...

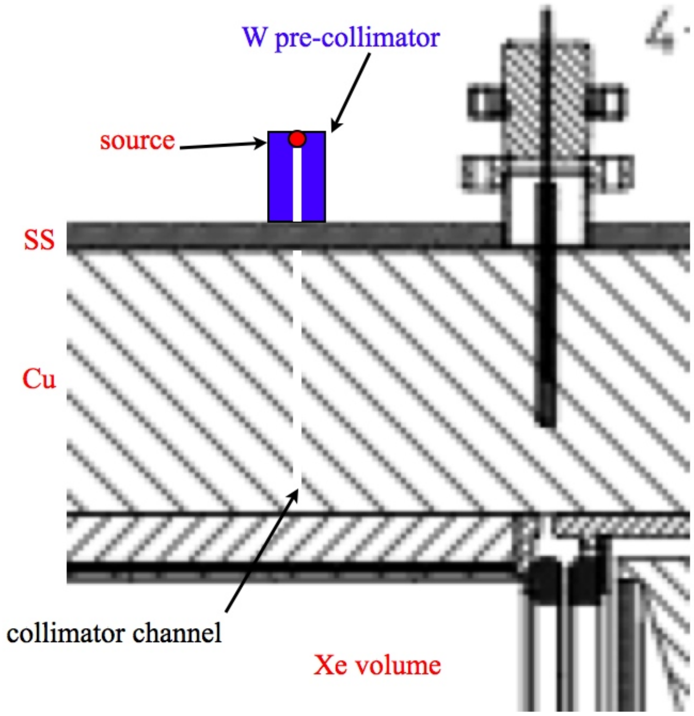

Figure 6: A tungsten (W) pre-collimator about 5-cm deep will be equivalent to the 20-cm of Cu shield. (fig:W-pre-coll)

3 Gaseous sources: $^{41}_{18}$Ar, $^{83}_{36}$Kr

Both $^{83}_{36}$Kr and $^{41}_{18}$Ar have half-lives of about 2 hours, and therefore can be metered into the Xe volume for calibration, then removed in the gas system, but in any case they are gone for the system in 8-10 hours.

The S_1 signal in NEXT will allow almost any source to be used, and this is a big advantage over other experiments, *e.g.*, the STAR TPC[1] that must use a random trigger in its calibration using ^{89}Kr decays.

Filling the TPC with $^{83}_{36}$Kr was used to calibrate the ALEPH TPC at LEP, the STAR TPC at RHIC, and now the ALICE TPC at LHC.

$^{41}_{18}$Ar $\rightarrow \gamma'$s at 1290 keV and 1680 keV

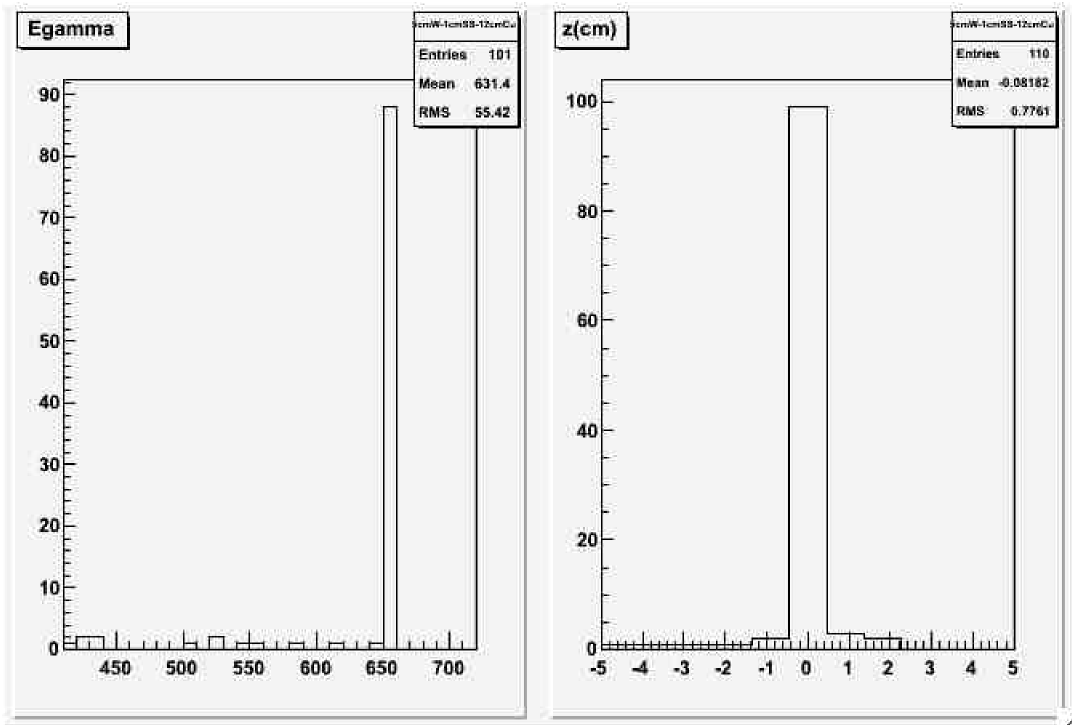

Figure 7: A $(1\text{mm})^3$ $^{137}_{55}$Cs source inside a tungsten pre-collimator outside the SS vessel, passing through the 1-cm thick SS, and aimed at a 2-mm diameter hole in the 12-cm Cu shield: γ energy distribution (left), and γ z distribution along drift direction (right). (fig:W-SS-Cu)

- Half-life $T_{1/2} = 1.827$ hours; Activity $= 4.184 \times 10^7$ Ci/g.
- ^{41}Ar gas can be metered into Xe volume, after equilibrium is reached the two γ's provide a relative average gain throughout (x, y) independent of attenuation.
- Two γ's allow a linear extrapolation to $Q = 2457.83$ keV.
- The $^{41}_{18}Ar$ must be prepared in a nearby reactor as

$$^{40}_{18}Ar\ (n, \gamma)\ ^{41}_{18}Ar \qquad \sigma_\gamma \sim 0.5\text{b}$$

- Requires a reactor, like for $^{24}_{11}$Na. Many hospitals have small reactors for local isotope production. Alternatively, a small $^{252}_{98}$Cf or $^{241}_{95}$Am neutron source could be built to make our own isotopes by the $n - \gamma$ reaction.

$^{83}_{36}\mathrm{Kr^m} \to \gamma$ at 41.6 keV

- Half-life is $T_{1/2} = 2.6$ h
- Liberated from solid Rb-83 with 124 d half-life.

The ALEPH collaboration metered $^{83}_{36}$Kr into the gas volume, calibrated, and in 2-3 half-lives of the 2.6h half-life $^{83}_{36}$Kr isotope, could take data. A plot of the simulated signal (left) and calibration data (right) are shown in Fig. 8. Maybe the energy of 41.6 keV is too low for NEXT, and maybe it is not precise enough for NEXT.

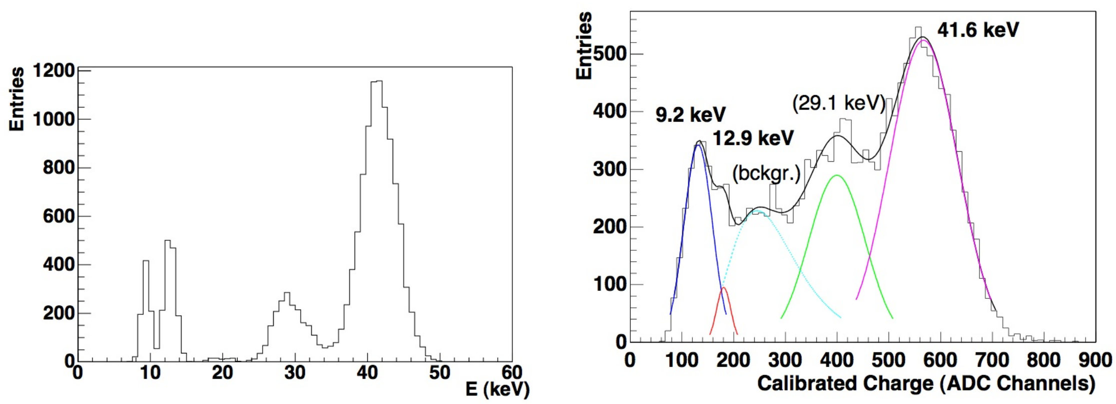

Figure 8: (a) Simulation of the expected $^{83}_{36}$Kr spectrum, and (b) measured spectrum. (fig:kalib)

4 Good but Dangerous Sources: $^{214}_{83}$Bi, $^{208}_{81}$Tl

These two nuclei decay to very convenient γ's near Q= 2457.8 keV: $E_\gamma = 2247$ keV, only 10 keV or $\sim 1\sigma$ below the Q value of $^{136}_{54}$Xe , and $E_\gamma = 2614$ keV, a comfortable amount above Q which is good for the high-end calibration, but it can contaminate the region-of-interest for escaping γ's.

The danger is that if *any* amount of these isotopes get loose inside or near the detector, there will be no experiment. In this section, we first list the properties of each, followed by how they might be used for calibration.

$^{214}_{83}\mathrm{Bi} \to \gamma$ at 2447 keV

Table 2: All $^{214}_{83}$Bi γ's above 1% rate. [3]

E_γ	BR(%)	E_γ	BR(%)	E_γ	BR(%)
609.3	46.1	1238.1	5.92	1729.5	3.05
665.4	1.56	1281.1	1.47	1764.5	15.93
768.4	4.88	1377.7	4.02	1847.4	2.12
806.2	1.23	1401.5	1.39	2118.6	1.21
934.0	3.16	1408.0	2.48	2204.1	4.99
1120.3	15.00	1509.2	2.19	**2447.7**	1.55
1155.2	1.69	1661.3	1.15		

- $^{214}_{83}$Bi is produced from the $^{238}_{92}$U series: when $^{214}_{83}$Bi is finally produced, its half-life is ($T_{1/2} = 20$ min)
- branching fraction = 1.55% (of all $^{214}_{83}$Bi γdecays; about 210 total decays)
- right near $Q = 2457.83$ keV (good)
- Activity = 4.41×10^7 Ci/g (pure $^{214}_{83}$Bi ??)
- $^{238}_{92}$U activity = 12,445 Bq/g = 0.34 μCi/g
- $^{214}_{83}$Bi activity reaches $^{238}_{92}$U activity at equilibrium 0.34 μCi/g
- a gram of $^{238}_{92}$U is a cube of size (2.5mm)^3

All $^{214}_{83}$Bi γ decays at rates higher than 1% are shown in Table 4, from [3]. Hence, a $^{214}_{83}$Bi source alone will have a bath of γ's from 600 up to 2450 keV, plus the other γ decay products from the U-series will contribute more γ's.

However, these additional γ's can also serve calibration as known points in the continuum of γ's below Q and inside the broad signal of $2\nu2\beta^-$, for example, the γ's at 609.3 keV, 1120.3 keV, and 1764.5 keV have high rates of 46%, 15%, and 16%, respectively.

The main problem is to balance the 2447-keV signal rate against the 70 times larger non-signal rate with saturates the DAQ.

Table 3: Properties of shielding metals used on the platform.

Element	ρ (g/cm^3)	σ_T (cm^2/g)	λ_{att} (cm)
Fe	7.87	0.03913	3.25
Cu	8.96	0.03871	2.88
SS	8.03	0.03919	3.18
Pb	11.35	0.04374	2.01

Table 4: Penetration probability for 2447-keV γ's in the shielding metals on the platform.

layer of material	thickness (cm)	$P(x)$
Fe (platform frame)	1.0	0.735
Pb (Castle shield)	20.0	4.77×10^{-5}
Cu (outer copper shield)	10.0	0.031
SS (pressure vessel)	1.0	0.735
Cu (inner copper shield)	12.0	0.0155

4.1 $^{214}_{83}$Bi as a point source outside the outer Cu shield

The density of the shielding materials, their cross section for the 2447-keV γ, and the attenuation lengths in each material are given in Table 4.1 for all absorption materials in NEXT in the table:

The probability to penetrate each layer of each shielding material of thickness x without scattering, $P(x)$, is shown in Table 4.1, ordered from outside to inside (thicknesses from Fig. 9.7 of TDR):

The penetration probabilities suggest that a $^{214}_{83}$Bi source could be placed inside the Pb Castle but outside the Cu outer shield, for example, by replacing a Pb brick of the Castle (on the side for each access, for example). Then the probability to reach the Xe volume would be

$$P([\mathrm{Cu}, 10\mathrm{cm}] + [\mathrm{SS}, 1\mathrm{cm}] + [\mathrm{Cu}, 12\mathrm{cm}]) \approx 0.031 \times 0.735 \times 0.0155 \approx 3.5 \times 10^{-4}$$

In secular equilibrium the activity of $^{214}_{83}$Bi in a $^{238}_{92}$U sample is 12,445 Bq per gram of $^{238}_{92}$U [4]. The Xe volume subtends about 10% of the solid angle, the probability

Table 5: Thallium ($^{208}_{81}$Tl) γ's that accompany the 2416-keV γ.

E_γ	BR(%)	E_γ	BR(%)	E_γ	BR(%)
10.5	1.3	84.8	1.27	763.1	1.64
12.7	1.22	277.3	6.80	860.3	12.0
72.8	2.14	510.6	21.6	2416.4	99.79
75.0	3.60	583.0	86.0		

to penetrate the Cu-SS-Cu shields is 3.5×10^{-4} and the convert in 1m of Xe is 1m/3m-attenuation-length = 1/3. Taking just the photoelectric conversions at 2%, the probability of a full-energy deposit is

$$3.5 \times 10^{-4} \times 12,445 \times 0.1 \times 0.02 \times (1/3) \approx 3 \times 10^{-3} Hz.$$

This is for one gram of $^{238}_{92}$U , or about a volume of (2.5mm)^3. To reach a rate of 1 Hz requires about 300 grams, or 15 cm^3 of $^{238}_{92}$U , which could be encased at the end of a wand to be inserted through a removable passage through the Pb Castle.

$^{208}_{81}$Tl $\rightarrow \gamma$ at 2614 keV

- come from $^{212}_{83}$Bi decay, ($T_{1/2} = 3$ min)
- branching fraction = 99.79%
- Activity = 2.956×10^8 Ci/g

The other γ's that accompany the 2614-keV γ are listed in Table 4.1.

The following sections are being worked on ...

5 Backgrounds, or More Sources, generated *in situ*

Both the Cu of the shield and the Fe in the SS will be activated by the cosmic μ's that do get through. I am going to just scale from the numbers in the note by Bonvicini [5]. For Cu that is un-activated when it is placed in Canfanc, depth 2450 mwe, the activities per tonne per day are

5.1 Surface activation

5.2 Subterranean activation

cosmogenic reaction	activity at 2450 mwe (ton^{-1} day^{-1})	NEXT activity/day
Fe $\rightarrow^{54}$Mn	2.25	2.7
Cu $\rightarrow^{60}$Co	0.48	4.3

These are quite low (if correct). The cosmogenesis activation rate is much higher on the surface, and so the production and transport times are important. Most of the stuff that is made [5] will decay away during the installation period of months.

6 Rates and Activities

Reality point in the LBNL prototype: 1 mCi $^{137}_{55}$Cs source collimated (near source) with Pb for 4 cm with an opening of 2 mm, placed 50 cm from the xenon volume produces 50 Hz of events with 2-3 Hz in the full energy peak (this fraction will change a lot for a bigger xenon volume, more full energy depositions).

At these γ energies between 0.662 MeV and 2.754 MeV, the photoelectric *pe* cross section relative to the Compton cross is not negligible, and the best calibration events will likely be the *pe* events. [2]

Let's take these events as the only useful events (although, the atomic de-excitations to a few low energy γ's can make this slightly off-energy (?)). A Xe K energy is 40 keV.

7 Spatial calibrations, efficiencies, and corrections

1. z-calibration —- need a known z position —- can use maximum drift, even if source is behind HV plane and Compton e- penetrate HV plane.

2. drift attenuation - exp(-z/a) - LBNL chamber a=

2.5 drift t z affected by diffusion: e- get ahead, or behind, ...

3. correct each time bucket .... c(r,z) c(r,t).

References

[1] "Calibration of the STAR Forward Time Projection Chamber with Krypton-83m," STAR Note-424, 31 July 2000. Also, a prior ALEPH paper on the same, D. Decamp, *et al.*, *Nucl. Instr. Meths.* **A294** (1990) 121.

[2] "Calibration of the STAR Forward Time Projection Chamber with Krypton-83m," V. Eckardt, *et al.*, arXiv:nucl-ex/0101013v2.

[2]The *pe* cross section goes like

$$\sigma_{pe} \propto \frac{Z^n}{E_\gamma^{7/2}},$$

where the power n is between 4 and 5, so take $n = 9/2$. Pegging this to the *pe* cross section on Pb $(Z = 82, \sigma_{pe} \sim 10\text{ b})$ at $E_\gamma = 1$ MeV (PDG figure, 27.14) the cross section on $^{136}_{54}$Xe can be written as

$$\sigma_{pe} \approx 10\text{ b} \times [\frac{54}{82}]^{9/2} \times [\frac{1}{E_\gamma}]^{7/2},$$

and at $E_\gamma = 2.5$ MeV is

$$\sigma_{pe} \approx 0.06\text{ b}.$$

The total Compton cross section at $E_\gamma = 2.5$ MeV is

$$\sigma_{\text{Compton}} \sim 0.35\text{ b}$$

So about 1/6 of the γconversions are photoelectric, *i.e.*, full energy and localized. The XCOM coherent cross section at $E_\gamma = 2.5$ MeV is about 0.6 b.

[3] "Table of Radioactive Isotopes," E. Browne, R. Firestone, and ed. V. Shirley (1986), but there are many editions.

[4] Website http://www.wise-uranium.org/rup.html.

[5] "Cosmogenesis Backgrounds, Experiment Depth and the Solar Neutrino TPC," G. Bonvicini, A. Schreiner, ArXiv:hep-ex/0203014v, 8 Mar 2002.

A Attenuation lengths of γ's in SS, Cu and Xe; and $\sigma_{pe}/\sigma_{\mathrm{T}}$

Table A.1 Cross sections on Xe and stainless steel (SS) for γ's from several sources. From this the attenuation length is calculated $\lambda(\mathrm{cm}) = 1/[\sigma_\gamma(\mathrm{cm}^2/\mathrm{g})\ \rho(\mathrm{g/cm}^3)]$ and, in turn, the probability to penetrate depth x without scattering is $P(x) = e^{-x/\lambda}$. The Xe is at 15 bar, and SS is taken to be 80%-Fe, 10%-Cr, 10%-Ni. Densities are $\rho_{SS} = 8.03$ g/cm^3, $\rho_{Cu} = 8.96$ g/cm^3, $\rho_{Xe} = 8.22 \times 10^{-2}$ g/cm^3. Cross sections from XCOM.

E_γ (keV)	Source	σ_{SS} (cm^2/g)	$\lambda^{SS}_{\mathrm{att}}$ (cm)	$P(x)$ 1cm	σ_{Cu} (cm^2/g)	$\lambda^{Cu}_{\mathrm{att}}$ (cm)	$P(x)$ 12cm $\times 10^3$	σ_{Xe} (cm^2/g)	$\lambda^{Xe}_{\mathrm{att}}$ (cm)	1-$P(x)$ 1m	$\frac{\sigma_{pe}}{\sigma_{\mathrm{T}}}$ %
662	$^{137}_{55}$Cs	0.07359	1.70	0.555	0.07259	1.54	0.41	0.07667	159	0.467	13.8
1173	$^{60}_{27}$Co	0.05535	2.26	0.642	0.05434	2.05	2.86	0.05239	232	0.350	6.0
1290	$^{41}_{18}$Ar	0.05274	2.37	0.656	0.05178	2.16	3.87	0.04965	245	0.335	5.3
1333	$^{60}_{27}$Co	0.05188	2.41	0.660	0.05093	2.19	4.17	0.04878	249	0.331	5.1
1368	$^{24}_{11}$Na	0.05120	2.44	0.664	0.05027	2.22	4.49	0.04812	252	0.328	4.9
1680	$^{41}_{18}$Ar	0.04630	2.70	0.690	0.04549	2.54	8.88	0.04363	279	0.301	3.7
2447	$^{214}_{83}$Bi	0.03919	3.18	0.735	0.03871	2.88	15.5				
2754	$^{24}_{11}$Na	0.03745	3.34	0.741	0.03705	3.01	18.6	0.03738	325	0.265	2.0