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Conceptual design for shielding the 200 μm-thick LBNL CCD at the Lick 3-m Coudé Spectrograph from environmental gamma radiation

This note was drafted by Don Groom (LBNL; `deg@lbl.gov`), but it is based on considerable work by Steve Holland, Dick McDonald, and Al Smith (LBNL), and by Richard Stover and Mingzhi Wei (UCO/Lick).

ABSTRACT

A 200 μm-thick LBNL CCD is being used by the Planet Search Group at the Lick Observatory's 3-m telescope Coudé spectrograph. Long dark exposures of the CCD show "cosmic ray" rates nearly four times larger than the irreduceable cosmic ray muon rate. We have shown directly that the unwanted artifacts are most likely recoil Compton electrons from environmental γ rays, from K and U, Th, and isotopes in their decay chains. (These elements are present in the concrete walls, for example.) We propose a simple tantalum shield with a silver lining inside the vacuum system, in order to reduce the Compton rate to approximately the muon rate. The compact design minimizes the mass, which might be optimized to under 3 kg.

1. Introduction

The radiation artifact counting rate in a horizontal CCD in an unshielded dewar in the Lick 3-m Coudé spectograph room is about 3 cm^{-2}min^{-1}, while the irreduceable cosmic ray muon rate is about 0.8 cm^{-2}min^{-1}. The difference is thought to be due to Compton electrons, the recoil products of environmental γ rays. Measurements with a γ-ray spectrometer identify these as direct γ rays from the decay of ^{40}K and from U, Th, and isotopes in their decay chains. A very important additional low-energy component is thought to consist of direct γ rays degraded by one or more Compton scatters in the material in the room. We have verified that the Compton-electron background can be reduced to about that of the cosmic rays with about 1 cm of lead shielding. Lead is not a very satisfactory material inside the dewar, so tantalum is proposed as an alternate. A thin silver lining reduces the fluorescence xray intensity from the tantalum.

2. Dewar shielding experiments

In 2000 September a series of long darks were made with a test LBNL CCD in an uncomplicated dewar sitting on the floor of the 3-m spectrometer room near the dewar position on the instrument. The CCD was horizontal. Lead shielding was gradually added. The results are shown in Fig. 1. The pattern recognition and analysis are discussed elsewhere [1]. From these results it was concluded that between 0.25 in and 0.375 in were sufficient to reduce the rate of the Compton events to about that of the cosmic rays, and that improvement beyond that level seemed marginal.

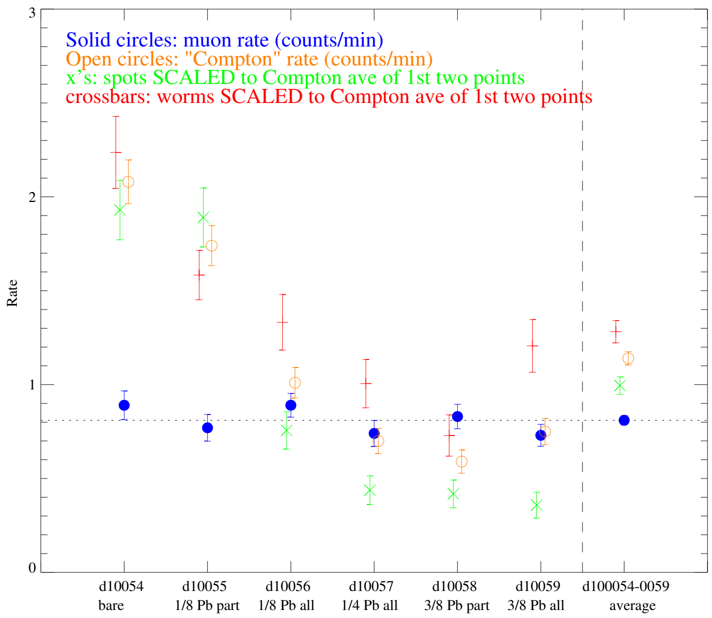

Figure 1: Rates of cosmic-ray muons and Compton electrons, and relative rates of worms and spots, in the Lick Observatory 3-m Coudé spectrometer room, as a function of increasing amounts of lead shielding around the dewar. This particular CCD was 200 μm thick. Note that the worm and spot rates have been scaled to expedite comparison with the total Compton flux.

The actual dewar for the instrument is considerably more complicated, with attached boxes and appendages, as can be seen in Fig. 2. A lead shield outside of the entire assembly, if attached to the spectrometer beam, would cause unacceptable deflection. Accordingly, Richard Stover and collaborators built a large (and massive!) 0.5 inch thick lead box on a cart, which could be moved in to more or less cover the dewar. The shielding was not exactly hermetic; there were numerous holes to accommodate the geometry, and the spectrometer beam itself was relied upon to provide shielding on the far side. Since the CCD plane was normal to the earth's polar axis, the cosmic ray rate was somewhat greater than in the case of the horizontal CCD, about 1.0 cm^{-2}min^{-1}. In the unshielded case the total rate was 3.3 cm^{-2}min^{-1}, consistent with the previous results shown in Fig. 1. But with the shielding box in place, the total rate was only reduced to 2.9 cm^{-2}min^{-1}, for a Compton rate nearly twice the cosmic ray muon rate. The lead box really didn't work.

The problem was investigated more carefully on 2002 Oct 30. The spectrometer dewar was on the cart (step-stairs with wheels), nearly on its side so that the CCD plane was near-vertical, with a north-south normal. The configuration is shown in Fig. 2. Lead 0.065 inch thick was progressively wrapped around parts of the rather awkward assembly, finally mimicking, as closely as possible, the case of 0.375 lead everywhere except for a hole for the light. The results are shown in Fig. 3. Within statistics, there was no change after exposure d231. The muon rate in a vertical CCD would normally be twice that observed in a horizontal CCD, but in this case near-horizontal muons experience considerable absorber (concrete, earth) before they arrive at the CCD. The Compton rate for images 231–235 averaged slightly above 1.0 cm^{-2}min^{-1}. The shielding was not as hermetic as it was in the 2000 September runs, so we regard the agreement with expectations as satisfactory.

The conclusion is that 0.25–0.375 inches of lead or its equivalent should be used. It is better err on the thick side.

Figure 2: Dewar 8 at the start of shielding tests on 2002 October 30. The tape and pads are to protect the window; no lead wrappings have yet been added.

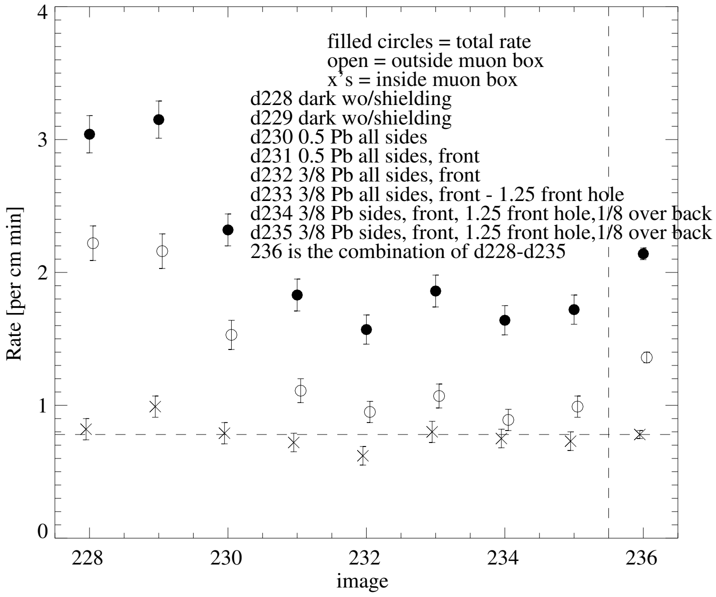

Figure 3: Total flux and flux of muon-like and Compton-like events in Dewar 8 in the Lick Lick 3-m Coudé spectrograph room for varying (mostly increasing) amounts of lead shielding. The shielding is never quite hermetic, so the levels are never as low as those achieved in Fig. 1. There is no significant difference from runs 231 to 235.

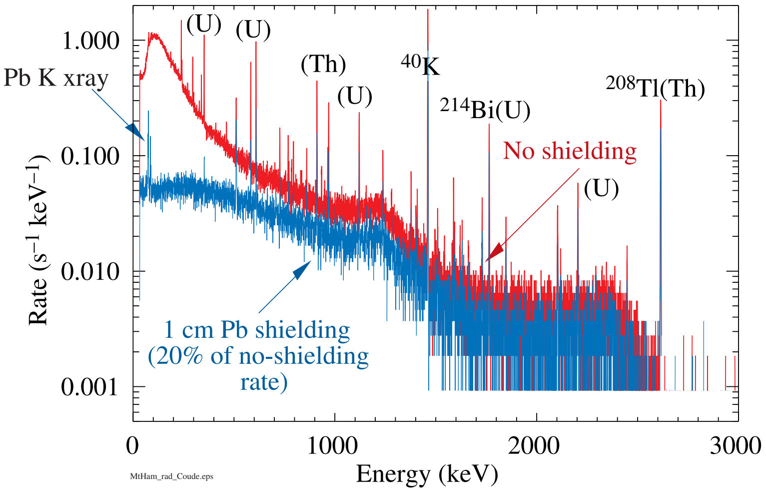

Figure 4: Gamma spectra in the Lick 3-m Coudé spectrograph room without and with a 1-cm lead shield. Characteristic lines correspond to gamma rays produced in ^{40}K decay and in the U and Th decay chains. Note the lead K x ray fluorescence lines at 73 and 75 keV.

3. Gamma spectrometer experiments

In 2001 June Al Smith *et al.*took a cryogenic gamma spectrometer to Mt. Hamilton. It consists of a depleted p-type germanium crystal approximately 8 cm in diameter and 8 cm long. The potential was applied between the lithium-drifted outer surface and a coaxial cylindrical hole. The outer

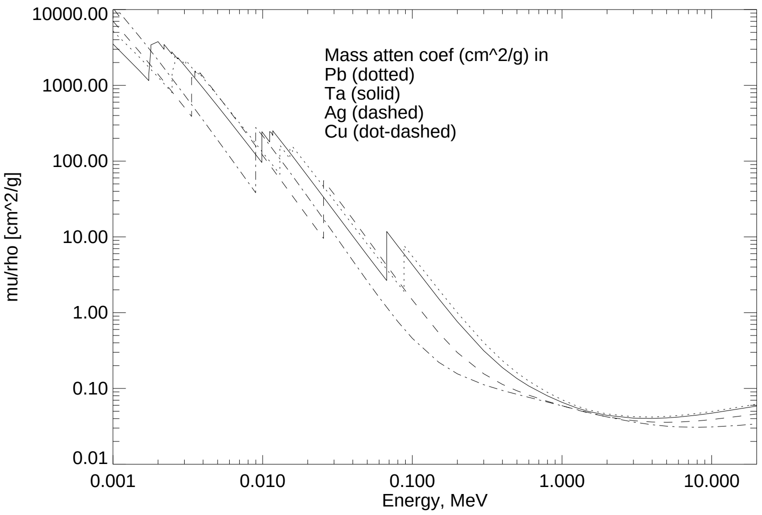

Figure 5: Xray (γ ray) mass absorption coefficients in lead, tantalum, silver and copper.

conductive layer, together with the enclosure (perhaps 0.0625 inch aluminum) strongly absorbs photons below about 100 keV.

Spectra were obtained in the Coudé room and on the 3m dome floor. In each location runs were made with the "naked" detector and with the detector inside a 0.375 inch Pb cylinder (with the open end blocked by Pb bricks). The spectra from the Coudé room are shown in Fig. 4.

If this detector is exposed to a monochromatic gamma source, one sees a very sharp peak at the source energy ("total containment," photoproduction or contained Compton scatters plus photoproduction) and a more-or-less flat plateau (due to Compton scattering) which extends up to the maximum energy that a Compton electron can acquire from the gamma ray. Since this energy is less than the energy of the gamma, there is a "valley" between the Compton edge and the total containment peak. Our incident spectrum is more complex, but it is dominated by ^{40}K peak at 1461 keV. The sharp peak, the Compton edge, and the valley between them are visible, albeit somewhat washed out by other distributions.

For the most part, the observed spectrum consists of the superposition of the spectra due to each monochromatic line. Except for ^{40}K, all of the peaks can be identified with photons from the decays of U, Th, and all their daughters. There is an important exception: the broad peak in the unshielded spectrum near 100 keV, which is understood as due to a "fog" of decay photons degraded by one or more Compton scatterings. The turn-down below 100 keV is an instrumental artifact, as explained above: Photons in this region are strongly absorbed by the inactive surface layer of the detector.

The "Compton fog" photons are very important for our problem. Not only is nearly 80% of the counting rate below 500 keV, but the probability that a photon will interact to make the Compton electron in the CCD falls sharply as the energy increases. (Examples of the mass absorption coefficient as a function of energy are shown in Fig. 5.) Killing the low-energy part of the spectrum is thus both necessary and sufficient. The combination of distribution and interaction probability also explains why 0.25–0.375 of lead is sufficient, even though more than 50% of photons above 1 MeV pass through the shielding without absorption.

This effect is shown by the with-shielding spectrum in Fig. 4. Only the low-energy part is killed, but the total number of counts is decreased by a factor of 5.

After the failure of the 0.5 inch-thick lead box, we again took the gamma spectrometer to the Lick spectograph, this time putting it very nearly in the dewar position. A variety of experiments were made with and without the lead box, with a lead cylinder around the spectrometer, with lead in front, etc. The results are summarized in Fig. 3. The lead box could not be pushed in all the way and the configuration did not exactly mimic the dewar/box geometry. However, the total counting rate was reduced by 0.56 and the rate below 500 keV by 0.52, more or less replicating the results with the CCD and dewar in place on the spectrometer.

Other experiments established that there was no significant radiation source in the I beam or in the thick glass mirror directly in front of the CCD.

The shielded spectrum shown in Fig. 4 also shows the characteristic K xrays from lead, most prominently at 72.8 and 74.9 keV. These x rays are not a problem if they are produced in shielding external to the dewar, since they are absorbed in the dewar walls or the window. If the shielding is inside the dewar, however, they will produce events in the CCD. The normal procedure is to used "graded shielding" of successively smaller atomic number to absorb the sequence of fluorescence x rays. In our case the effect is already minor, so we are proposing only one secondary absorber, a thin silver layer.

4. Shielding material

While lead is cheap and easy to use, it is understood to be unsuitable in high vacuum applications. We wish to use a material which has as high an atomic number as possible, and (a) is not too expensive, (b) does not have unpleasant chemical or radiological properties, (c) is unlikely to have radioactive trace impurities like U or Th, and (c) has good vacuum properties. Criteria (a) and (b) eliminates the next 7 lighter elements (Tl, Hg, Au, Pt, Ir, Os, and Re). Tungsten is a viable candidate, although there is mixed experience with baking and outgassing it [4]. Domestic tungsten is also reported to have U and Th impurities [3].

The next element, at $Z = 73$, is tantalum. Apparently separation of Ta from Nb is difficult, and requires several chemical steps [5] which preclude U and Th traces; it is reported to be radiologically clean [3]. It is ductile and inert [5]. According to a market report, it cost $60 to $80 per pound as of September 26, 2001 [2]. However, its price has fluctuated wildly over the years. Higher-purity tantalum is obviously more expensive, but if the impurity is just niobium it is not a problem.

On this basis, we recommend tantalum for shielding inside the dewar.

5. Gamma rays in tantalum

Gamma ray mass absorption coefficients for a number of materials are shown in Fig. 5 [6]. We prefer a large coefficient in the 100–500 keV (at lower energies all moderately heavy materials have a very large coefficient). It can be seen that tantalum is nearly as effective as lead.

Fig. 6 shows the survival probability of gammas in 0.375 inch lead (solid line), and the same quantity for tantalum with its thickness adjusted to obtain the same value at 1 MeV (0.711 cm = 0.28 in).

It is desirable to absorb the tantalum fluorescence xrays emerging from the back of the shield. The ideal absorber is holmium; the closest realistic absorber is silver. Fig. 7 shows a blowup of Fig. 5 in the region of interest, showing the positions of the tantalum K xrays and the intercepts with

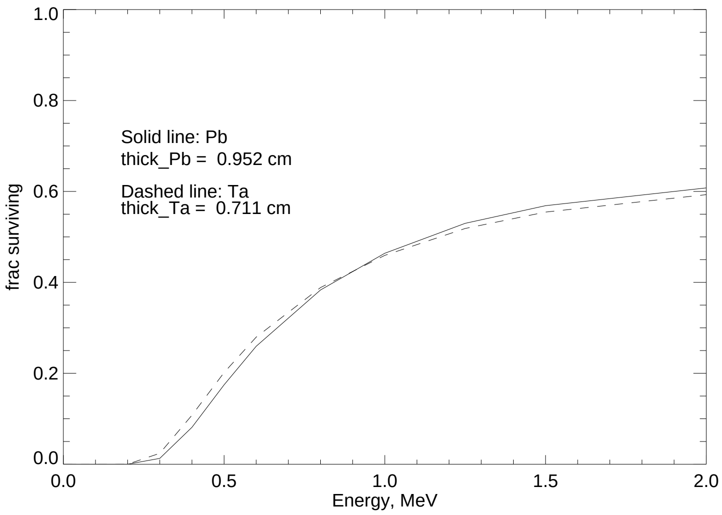

Figure 6: Survival probability of photons normally incident on 0.375 inches of lead and 0.28 inches of tantalum. The tantalum thickness was chosen so that the probabilities at 1 MeV would be the same.

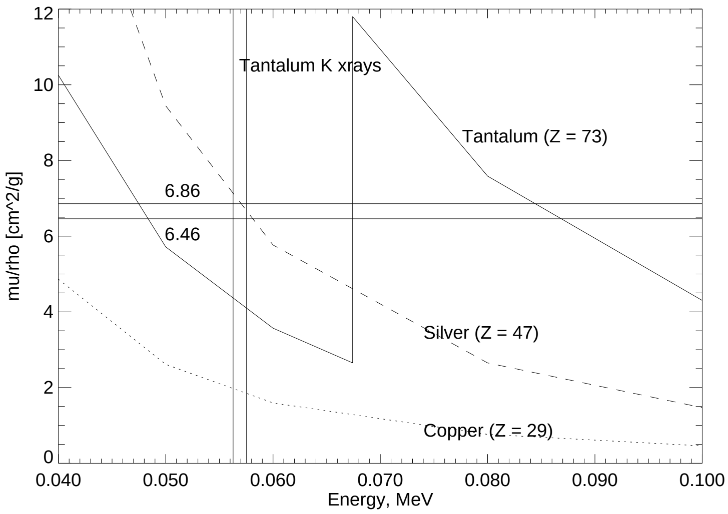

Figure 7: Detail of the absorption coefficient near the K edge in tantalum, showing the xray fluorescent K xrays from the tantalum and their mass absorption coefficients in silver.

the silver absorption curve. A foil 0.015 inch thick provides 2.6 absorption lengths for the highest-energy xray. The problem is minor and the silver fluorescence xrays are emitted isotropically, so we see litte reason to continue with a graded shield.

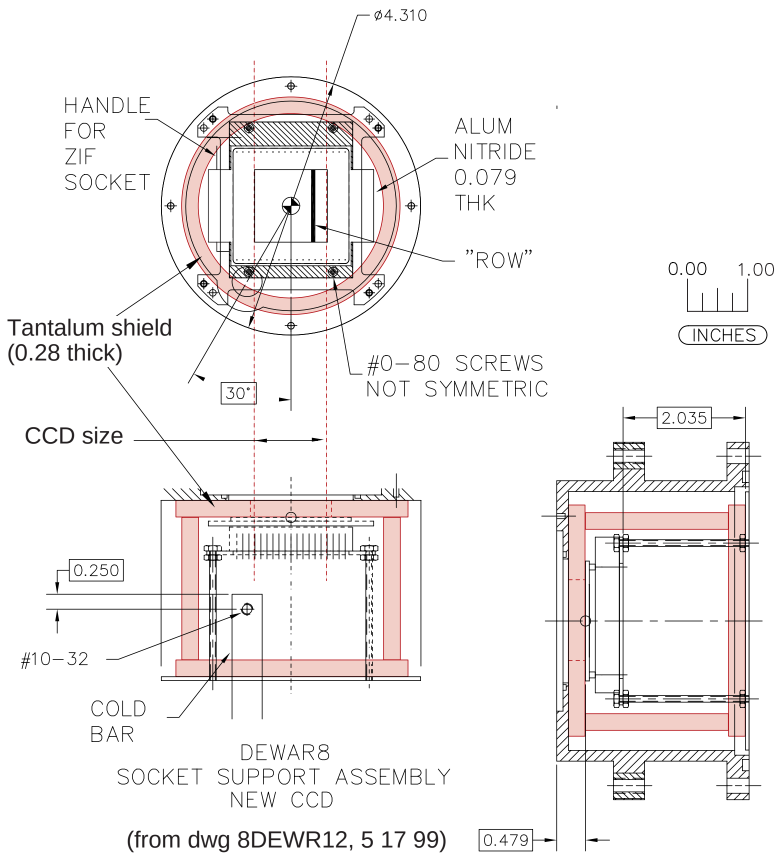

Figure 8: Crude conceptual design for shielding the Dewar 8 CCD at the Lick 3-m spectrometer. This configuration weights 3.5 kg, but a more minimal volume configuration can be expected.

6. Conceptual design

Drawings of Dewar 8 were obtained from Richard Stover, and Fig. 8, based on part of drawing 8DEWR8, shows relevant views of the "hat." Details of the spider top plate are shown in drawing 8DEWR16. The spider probably interfers with the tantalum shield which we show, but in any case the shield will need to be carefully engineered to fit and to minimize the mass. We have simply shown a tantalum cylinder 0.28 inches thick whose ID is larger than the diagonal of the AlN wafer to which the CCD is bonded, and circular "caps." A square hole in the top cap is large enough not to vignette light, allowing for alignment errors. Not shown are holes in the bottom circle for the cold bar and wiring. Obvious, the bottom circle might be split to expedite assembly.

As shown (without further holes), the mass of the cylinder is 1.89 kg, and the mass of the two circles with a square hole in the top one is 1.66 kg, for a total mass of 3.55 kg. We note that the mass of the cylinder could be halved by mounting the bottom circle as high as possible on the standoff screws instead of at the bottom. In addition, there is no reason not to replace the cylinder by four rectangles; this would also reduce fabrication costs.

As we have noted, the 0.375 inch Pb-equivalent tantalum thickness is also arbitrary; our measurements do not distinguish clearly between 0.25 and 0.375 inches of lead.

Inside the tantalum is a silver lining at least 0.015 inches thick.

7. References

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