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Neutron Radiation Damage in Comparison to EM Damage at the SSC

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1. Introduction

Much effort has been put into estimating the maximum radiation dose at the SSC [1]. That dose is due to the "minimum bias" events which contain large numbers of low Pt photons from π^0 decays. The charged pions from minimum bias events also deposit energy in the calorimeters of SSC detectors. The dose is reduced with respect to the EM dose even though the charged pion energy/event is roughly twice the neutral pion energy. This reduction is due to the fact that dose is by definition the deposited energy/mass and the radiation length is less than the interaction length. For example, in iron, that ratio is roughly 10. In particular, in the SDC detector [2], the dose in the hadronic calorimeter, HAD, is roughly 1/5 of the dose in the electromagnetic calorimeter, EM, at the same angle.

There is another effect which has received somewhat less attention. A hadronic shower in material is known to leave a considerable fraction of its energy in the form of nuclear excitation (binding energy losses) [3]. That energy eventually appears in the form of slow neutrons after nuclear deexcitation and inelastic neutron scattering. Calorimeters employing scintillator as the active medium are then at some risk. The sea of slow neutrons has a large cross section, of order 10 barns (!) at 1 MeV kinetic energy, to elastically scatter off the quasifree protons in the plastic. That scattering is a very efficient method of energy transfer to the detecting medium of the calorimeter. For this reason, a first tentative estimate of the neutron damage possibilities appears to be called for [4]. Experimental measurements of the neutron fluence [5] have been obtained, and more refined Monte Carlo studies [6], have recently been started.

2. EM Dose Estimate

The EM dose can be estimated fairly accurately from elementary considerations. Suppose inclusive interactions produce pions with a mean transverse momentum, $<P_T> =$ 0.75 GeV. Assume that inclusive production occurs with a rapidity "plateau" of density D hadrons per unit of rapidity. Take as a simple model of the calorimeter a solid surrounding a cylindrical void of radius r_o and half length z_o. The energy crossing an area element dA, given a total inelastic rate R_I acting for a time t, is then;

$$E = (R_I t) D \left[\frac{dA}{2\pi z_0^2} \right] \left[\frac{< P_T >}{\sin^3 \theta} \right] \tag{1}$$

for illumination of the "endcap" region.

Note the characteristic cubic dependence on angle. The neutral energy is assumed to be E/3. Suppose that the shower in Pb/scintillator deposits Nmip ~ 10 mip/GeV at shower maximum [3]. The scintillator absorbs energy due to ionization in the plastic. Since radiation dose is simply the energy deposited per unit weight, the EM dose is then;

$$(Dose)_{EM} \sim (R_I t)(D/3) \left[\frac{dE/dz}{2\pi z_0^2} \right] \left[\frac{< P_T >}{\sin^3 \theta} \right] N_{mip} \tag{2}$$

where dE/dz is the mip energy deposit in $MeV/(gm/cm^2)$.

Numerical estimates can now be made for the SSC. At design luminosity, $R_I =$ 100 MhZ. Assuming a "standard" SSC running year of 10^7 sec, $R_I t = 10^{17}$ interactions in a 100 year "lifetime" period at design luminosity. The dose conversion factor is 1 Mrad = 6 x 10^{13} MeV/gm. Taking a density of D = 7 particles per unit of rapidity, a mean transverse momentum of <Pt> = 0.75 GeV, a detector with $z_o = 4.2$ m, and the previously stated estimate for Nmip, one obtains for pseudorapidity = 3;

$$(Dose)_{EM}^{\eta=3} \sim 52 Mrad \tag{3}$$

A simple extension of Eq. 2 yields the dose at $\eta = 0$ of 0.23 Mrad. These very naive estimates are in good agreement with more detailed calculations [2]. It is, therefore, clear that the EM dose can be understood by simple techniques. The hadronic dose can then be easily obtained by appealing to the relative longitudinal energy deposit profiles of photons and hadrons [2].

3. n Fluence Estimate

The neutron fluence is rather more complicated. One of the processes involved in hadronic showers is the excitation of the nuclei of the absorber material. Neutrons are emitted in the deexcitation process. These neutrons interact by a variety of inelastic processes and lose energy. At a kinetic energy of ~ 1 MeV, the inelastic channels close. The elastic scattering off heavy nuclei results in only minimal energy transfer. The neutrons then "decouple" since the absorber (say steel) is transparent to neutrons. Therefore, the neutrons leak out of the detector with a "universal spectrum" [1] having a kinetic energy T ~1 MeV. This expectation has beeen verified many times [7]. A spectral plot taken from Ref. 7 is reproduced in Fig 1. In shielding piles one typically uses hydrogenous materials to "moderate" the neutrons, thus, using elastic scattering to reduce the n energy below the 1 MeV value.

The yield of n in a hadronic cascade can only be extracted from a very detailed Monte Carlo simulation. The results of such a program are given in Ref. 1. A plot from that study is reproduced in Fig. 2. An extremely simple (good to a factor ~ 3) parametrization of the results shown in Fig. 2 is;

$$\begin{aligned} &< n > \sim 6\left[E(GeV)\right]e^{-(\lambda-2\lambda_o)/\lambda_{EFF}} \\ &\lambda_{EFF} / \lambda_0 \sim 0.67\left[E(GeV)\right]^{0.33} \end{aligned} \tag{4}$$

At the lowest level, we expect N_n = 6 neutrons/GeV of incident energy for the first 2 interaction lengths of depth of the calorimetry.

The 1 MeV neutrons have a large elastic scattering cross section. The data, [8], indicate a spectrum which goes essentially as 1/T. A rough parametrization of the data is;

$$\sigma_{np} \sim 7\,Barn / \left[E(MeV)\right]^{0.84} \tag{5}$$

This means, for example, that a 1 MeV neutron has a ~ 7 barn cross section for elastic scattering. Note that, in an elastic scatter off a nucleus with atomic number A, the typical n final energy T for an incident energy T_O is;

$$T \sim To(A-1)/(A+1) \tag{6}$$

Clearly, only the free protons in the calorimeter can receive significant energy in elastic scatters with the neutrons. If only heavy nuclei exist in the calorimeter, the neutrons will leak out without elastic scattering or "moderation". Clearly, for large A the final energy T is ~ the incident energy T_o.

The n fluence, F, estimate then follows from some more over simplifications. Assume that the source of neutrons is charged pions, which yield N_n neutrons per GeV, and which do not diffuse transversely. Obviously, the assumption of contained transverse motion is not very plausible. In any case, the fluence estimate under this assumption is;

$$F_n = E(2/3)N_n \tag{7}$$

Numerically, in a 1 year time interval, the fluence is estimated to be $F_n = 8 \times 10^{10}$ n/cm^2 at $\eta = 0$ and 2×10^{13} n/cm^2 at $\eta = 3$.

For comparison, the estimate given in Ref. 1 is shown in Fig. 3. The cubic dependence on angle implied by Eq. 1 is clearly in evidence. The fluence at $\eta = 0$ is about a factor 4 higher than the estimate made on the basis of Eq. 7. The result at $\eta = 3$, scaled as radius squared, is a factor ~ 2 higher than the estimate made on the basis of Eq. 7. The prediction from Ref. 6 is that F_n is 1.8×10^{12} n/cm^2 yr at $\eta = 0$ and 1.6×10^{13} at $\eta = 3$. The dependence implied by Eq. 1 means that the fluence at $\eta = 5$ is ~ 400 times larger than the fluence at $\eta = 3$. That strong angular dependence is confirmed in Ref. 6. It appears that the crude estimate does well at small angles, but may fail at large angles.

One can speculate that the assumption that the n are fixed at the impact point of the hadron is at fault. If the n are mobile, then many more will diffuse into large angles than will diffuse into small angles, given the great disparity in production rates of neutrons as a function of angle. Clearly, if the n are mobile, they will tend to "fill in" the regions of low fluence. Obviously, the degree of mobility is very dependent on the details of the construction of the individual detectors.

4. EM/n Dose Ratio

One can also compare the n and EM radiation doses. The ratio of doses may be more accurate since the "flux" cancels out in that ratio. Consider a 1 MeV neutron incident on a scintillator. The probability to elastically scatter then follows from Eq. 5. For S wave scattering, one can assume that the proton recoils with $\langle E_n \rangle/2$ or 0.5 MeV kinetic energy. To set the scale, a 1 MeV neutron has a ~ 13% probability to elastically scatter when normally incident on a 4 mm polystyrene plate. Therefore, it seems as if a scintillator based calorimeter will absorb many of the 1 MeV neutrons produced in the hadronic cascades.

Under these assumptions, an integrated n fluence of 10^{13} n/cm^2 deposits a dose of 0.03 Mrad in the scintillator due to elastic proton recoils, as given in Eq. 8 below.

$$(Dose)_n = \left(F_n \frac{N_0 \sigma_{np}}{A} < E_n > /2 \right) \tag{8}$$
$$F = 10^{13} n / cm^2 \equiv 0.03 Mrad$$

The dose ratio for EM and n damage follows directly from Eq. 2 and Eq. 8. That ratio does not depend on the inclusive "flux" of charged and neutral pions. The ratio depends only on the different physical processes of energy deposition in the two cases. For the EM shower it is ionization, while for the hadronic showers, the neutrons elastically scatter of the quasifree protons in the scintillator plastic. Note that the hadronic shower has its own ionization products. The peak dose in the SDC steel hadronic calorimeter is only 1/5 of the peak damage in the Pb EM calorimeter [2].

$$\frac{(Dose)_{EM}}{(Dose)_n} = \frac{N_{mip}(dE/dz)}{N_n \left(\frac{N_0 \sigma_{np} < En >}{A} \right)} \tag{9}$$
$$\sim 10$$

The ratio is ~ 10. This means that the n dose in the EM calorimeter is minimal with respect to the ionization dose. However, the n dose in the hadron calorimeter is 1/2 the ionization dose.

5. Conclusions

The implications of the n fluence has been examined. Scintillator based calorimeters are particularly at risk, due to elastic proton recoils. The EM calorimeter has a total dose which is overwhelmingly dominated by ionization. For the hadronic calorimeter, the ionization dose still is a factor ~ 2 larger than the n dose. Given the crudity of the assumptions used here, the n dose should be Monte Carlo simulated much more accurately. Obviously, the estimate made here is only good to an order of magnitude, at best.

In addition, the wide angle doses may be larger than have been estimated previously. The 100 year ionization dose in the EM is 0.23 Mrad at $\eta = 0$ and 52 Mrad at $\eta = 3$. The ratio of the doses at the 2 angles is ~ 225. The hadronic dose due to ionization is 0.05 Mrad at $\eta = 0$ and 10 Mrad at $\eta = 3$.

The fluences given in Ref. 1 and Ref. 6 are in fair agreement at $\eta = 3$. However, the fluence at $\eta = 0$ differs quite a bit. In Ref. 6 the fluence at $\eta = 0$ is only down from the fluence at $\eta = 3$ by a factor ~ 8. Using Eq. 8 and the fluences given in Ref. 6, the dose due to neutrons is then 5 Mrad at $\eta = 3$ and 0.6 Mrad at $\eta = 0$. The hadronic dose due to neutrons is only 1/2 that of the ionization dose at $\eta = 3$. However, the hadronic dose due to n at $\eta = 0$ is 12 times the hadronic dose due to ionization, if the fluence given in Ref. 6 is correct.

Therefore, the dose at small η may have been seriously underestimated. Clearly, the details are going to be very detector dependent. It is of some importance to accurately evaluate the neutron fluence at wide angles in any SSC detector, in particular, those detectors with plastic scintillator as the active medium.

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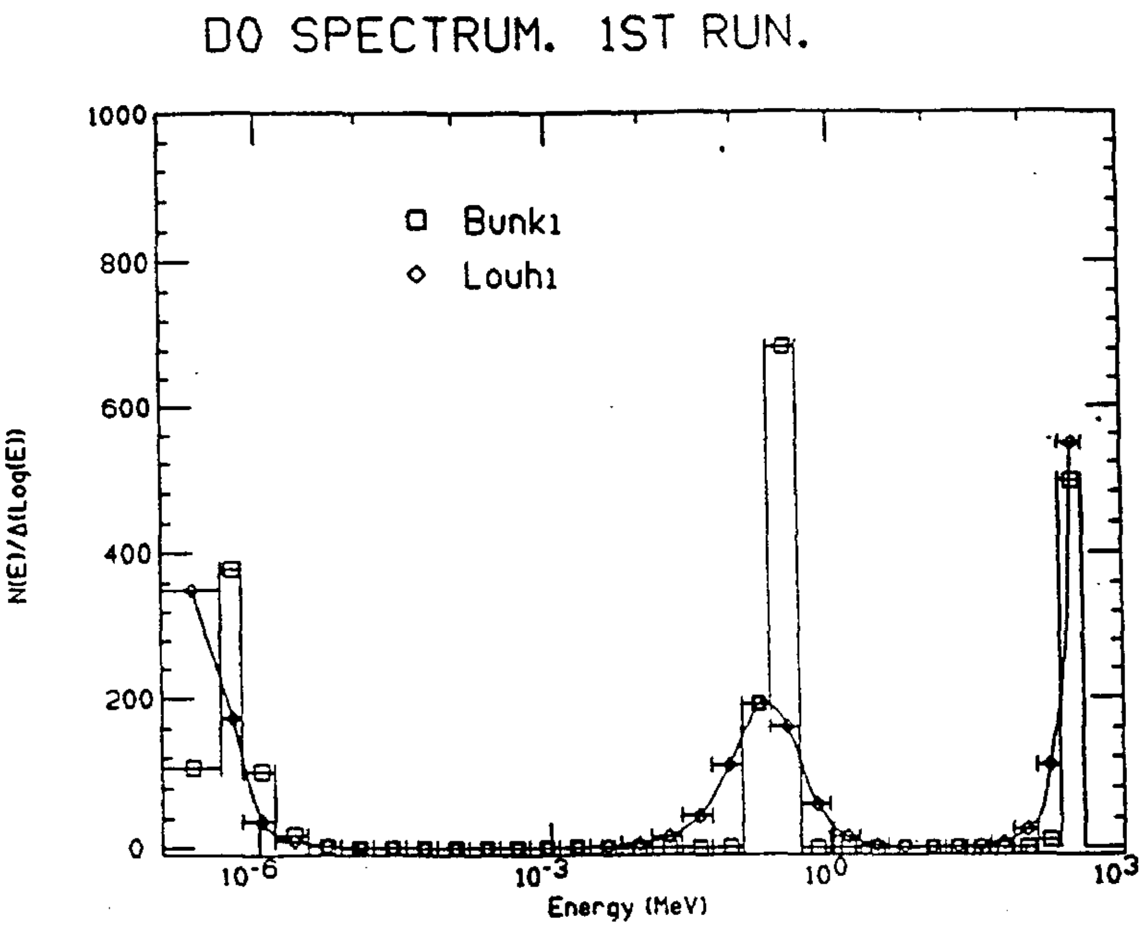
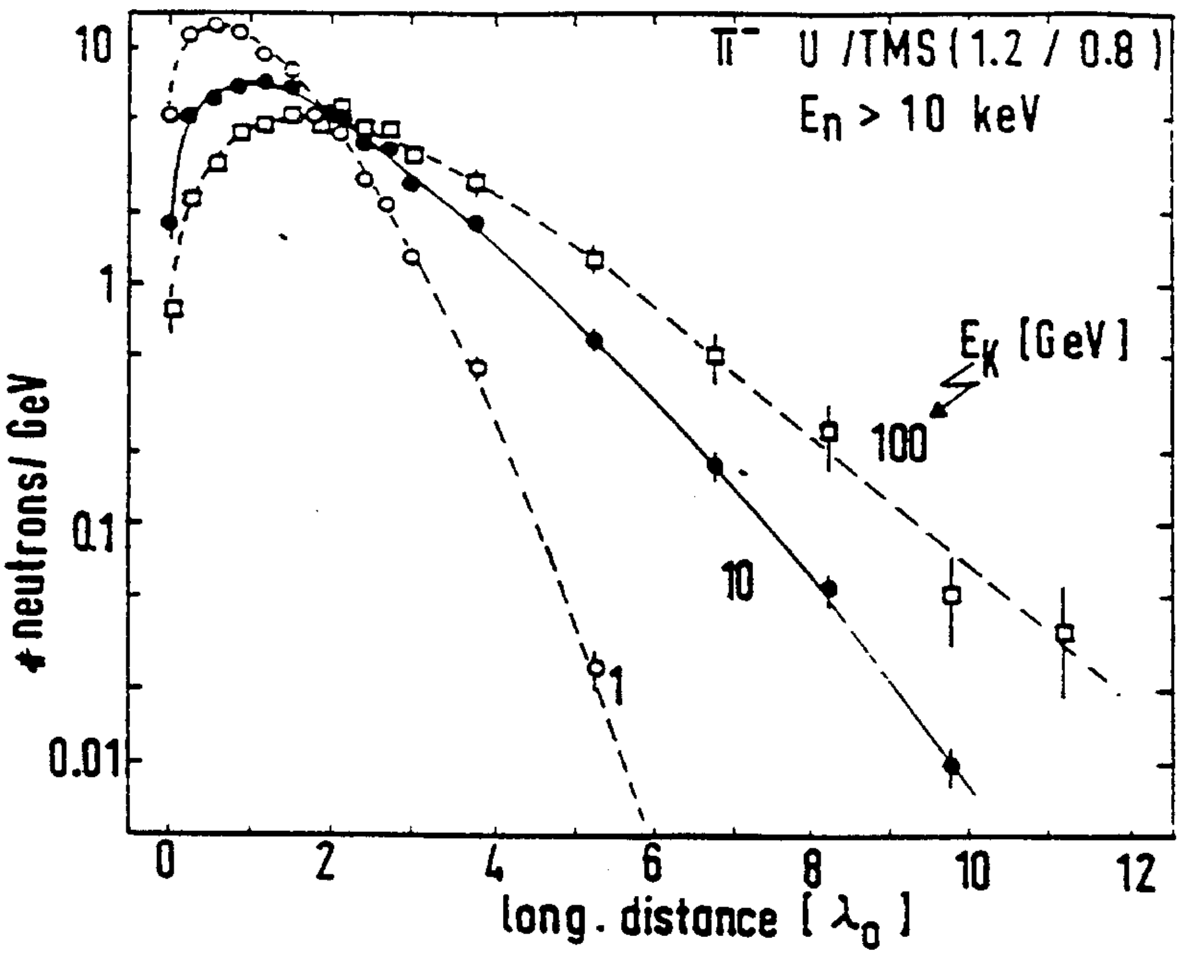
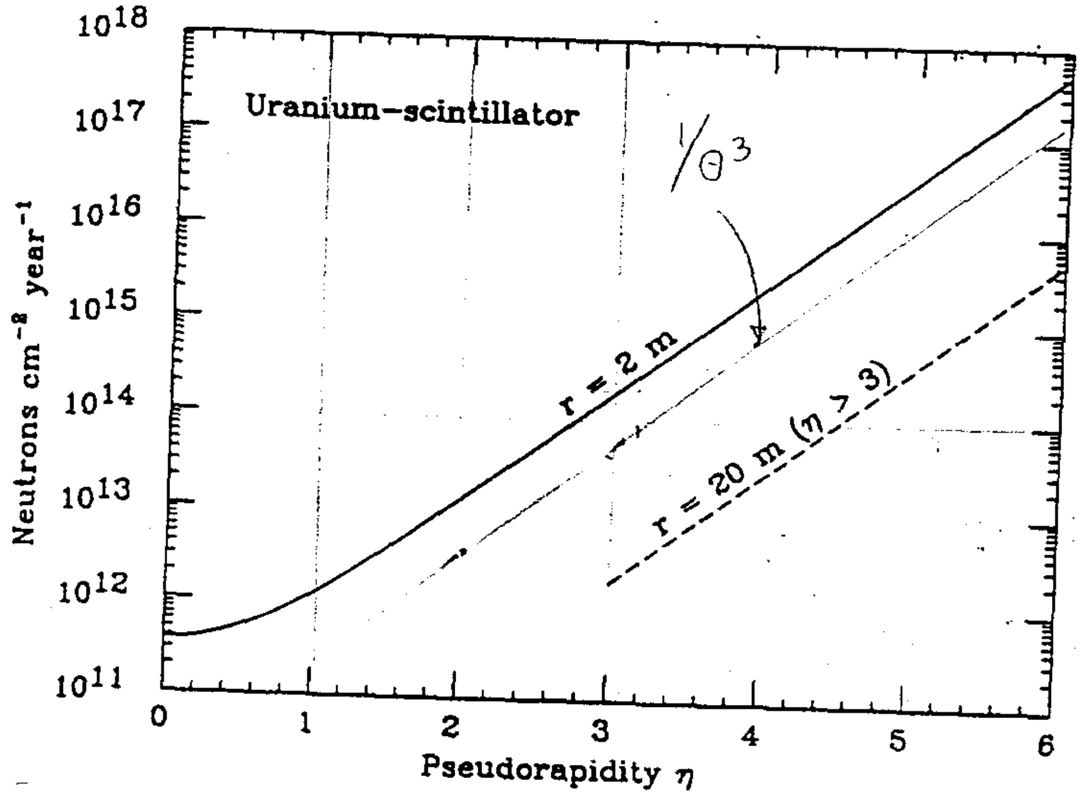


1. Measured n spectrum from the D0 collision hall study cited in Ref. 7. Note the characteristic peaking of the n spectrum at T ~ 1 MeV.



2. Monte Carlo results quoted in Ref. 2 for the yield of neutrons in an hadronic cascade as a function of depth within that cascade. Plots for 3 representative energies are shown.



3. Figure 5-4 reproduced from Ref. 1. The calculated neutron fluence for a U/scintillator as a function of pseudorapidity is shown. A spherical cavity of radius r = 2m has been assumed.