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Comments on the Determination of Transverse Shielding for Proton Accelerators

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Summary: In a recent paper Stevenson, Kuei-Lin and Thomas (St81) have reviewed estimates of transverse shielding for high-energy proton accelerators. Additional remarks are given concerning some simplifications in calculating dose-equivalent rates and the shielding properties of iron.

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An estimate of the dose equivalent outside the shielding of a high-energy proton accelerator can be made by using simple expressions if the shielding material is earth or ordinary concrete. The attenuation of the relevant secondary radiation - mostly neutrons - is a complicated process, but its description is usually be simplified by making the following assumptions:

(1) The shielding is thick enough to absorb primarily produced low-energy neutrons (evaporation neutrons, for example).

(2) The dose outside the shield is caused by high-energy neutrons (E_n > 100 MeV) and by the low-energy neutrons being in radiation equilibrium with them. The attenuation length of the dose then equals that of the propagating particles.

(3) For a point target only the angular region $60 < \theta < 120^{\circ}$ with respect to the beam is considered. Here the angular distribution of secondaries produced in the target is assumed as exponential with a relaxation parameter being independent of the primary proton energy; the spectrum of neutrons in the shield, the attenuation length of the propagating neutrons and the relevant fluence-to-dose conversion factor are assumed to be independent of θ (and of E_p).

(4) The dose is proportional to the energy of the primary proton beam and independent of target geometry and target material.

The assumptions 1 to 3 are known as the Moyer model. They allow to write the dose-equivalent rate outside the shield of a point-like target as

$$H = H_o e^{-\beta\theta} \quad L \frac{e^{-\frac{d}{\lambda}}}{r^2} \quad , \qquad (1)$$

where L is the energy deposited in the target per unit time, d and r are shield thickness and distance, and H_o, β and λ are parameters to be determined experimentally.

In a recent paper Stevenson, Kuei-Lin and Thomas (St 81) carefully reexamined the results of several point-source experiments and found as best values:

$\beta = 2.3$ in the range $60^o < \theta < 120^o$, $\lambda = 117$ g cm^{-2} for earth or ordinary concrete, $H_o = 1.03 \cdot 10^{-3}$ Sv m^2 J^{-1}= $5.9 \cdot 10^{-5}$ (mrem/h) m^2/(GeV/s).

With these data it follows from eq. 1 that the maximum dose occurs at angles somewhat smaller than 90^o, but for practical room dimensions this maximum is only by less than a factor of two larger than the dose at 90^o. For 90^o we have

$$H = 1.6 \cdot 10^{-6} L \frac{e^{-\frac{d}{117}}}{r^2} \; ; \quad \begin{array}{l} H \text{ (mrem/h)} \\ r \text{ (m)} \\ d \text{ (g/cm}^2) \\ L \text{ (GeV/s)} \end{array} \qquad (2)$$

It should be emphasized that eq. 1 - together with the parameters mentioned above - is limited to angles between 60^o and 120^o. Below 45^o the angular distribution becomes much steeper than the exp$(2.3\ \theta)$ dependence (see e.g. Le 72), and also the attenuation length increases (Ca 67). For a point source the Moyer picture is limited to values around 90° where an expression like eq. (2) with experimentally determined parameters is quite obvious.

In many cases a line source is a better approximation of the beam loss in an accelerator. Then eq. (1) can be integrated along the line source (Ro 76). This integration is performed over the total angular range from 0° to 180°. The resulting integral $M(\beta, \frac{d}{\lambda})$ is known as a Moyer integral, and for the dose rate from a line source the expression

$$H = H_o \frac{\bar{L}}{r} M(\beta, \frac{d}{\lambda}) \qquad (3)$$

is received, where $\bar{L}$ is the beam loss per unit time and unit length.

This expression can be converted to the familiar line source expression. In the interesting region 2 λ to 15 λ the integral is well approximated by

$$M(2.3, \frac{d}{\lambda}) = 0.065 \; e^{-1.09 \frac{d}{\lambda}} . \qquad (4)$$

Then for a line source

$$H = 5.9 \cdot 10^{-5} \cdot \frac{\bar{L}}{r} \cdot 0.065 \; e^{-1.09 \frac{d}{117}}$$

$$= 3.9 \cdot 10^{-6} \; \bar{L} \cdot \frac{e^{-\frac{d}{107}}}{r} ; \; \bar{L} \; (\text{GeV/s m}) \qquad (5)$$

Though such an expression is expected for a line source, it is not simple to estimate the validity of it. In integrating from 0° to 180° one leaves the range of validity of assumption 3 stated above. The fact that experimentally determined parameters are used in eq. 1 does not necessarily prove the validity of eqs. 3 and 5, since the abundant and highly penetrating particles at smaller angles are not properly be taken into account.A direct experimental check has not been made since it is difficult to realize a well-defined line source. Therefore it is useful to compare both eq. 2 and eq. 5 with the results of a theoretical treatment of the side shielding problem.

A good theoretical treatment is due to O'Brien (OB68, OB69). Both for a point source and a line source he gives expressions for the neutron dose rate behind an accelerator shielding, in which the effect of the shield is described by barrier factors B(d). These factors are independent of the distance between source and shield and are used by the author for proton energies up to 300 GeV. The barrier factor for earth (simulated by aluminum + 6% water) can also be simplified; in a very good approximation it is

$$B(d) = 6.8 \cdot 10^{-8}\, e^{-\frac{d}{103}} \quad ; \quad d\ (\mathrm{g/cm^2})$$

$$\text{for } d > 100\ \mathrm{g/cm^2}.$$

With this approximation the results of O'Brien assume a particularly simple form and are compared in the following synopsis:

	point source	line source
Stevenson et al. (St81)	$H=1.6\cdot 10^{-6}\, L\dfrac{e^{-\frac{d}{117}}}{r^2}$	$H=3.9\cdot 10^{-6}\,\bar{L}\,\dfrac{e^{-\frac{d}{107}}}{r}$
O'Brien (OB68)	$H=3.9\cdot 10^{-6}\, L\dfrac{e^{-\frac{d}{103}}}{r^2}$	$H=7.8\cdot 10^{-6}\,\bar{L}\,\dfrac{e^{-\frac{d}{103}}}{r}$

H(mrem/h) ; L(GeV/s); $\bar{L}$(GeV/s m);
d(g/cm^2); r(m)

The agreement between theory and the summary of several point-source experiments is remarkably good. For an earth shielding between 100 and 1500 g/cm^2 the dose rates differ not more than by a factor of two from each other for each source geometry, and this error is not bigger than the error introduced by the uncertainty in the density and in the water content of the earth. The error in H will mainly be due to the error made in estimating (or better: in guessing) the beam loss along the accelerator, L or $\bar{L}$, the error of which is larger than a factor of two in any case. In view of these uncertainties it seems that the simple expressions can be used with confidence in the case of an earth or ordinary concrete shielding.

In contrast to these materials, the shielding properties of iron for high-energy proton accelerators are not well established.

Conventional accelerators never have a pure iron shielding, but for a particular experimental set-up, especially at storage rings with their low mean beam power, the problem of calculating the dose equivalent behind a thick iron shield can arise. In their review article Stevenson et al. use an attenuation length of 147 g/cm^2 which roughly equals the nuclear mean free path for absorption in iron. This is a suitable value when applied to a relatively thin iron shield (e.g. a dipole magnet) inside a thick earth shielding. When it is used as a dose attenuation coefficient for a pure iron shielding, the dose equivalent will be underestimated because of the high build-up of neutrons below 1 MeV. Many years ago it has already been observed at the proton accelerator in Dubna (Sy66) that in an iron shield the radiation equilibrium between high-energy neutrons and resonance-neutrons is not established up to a depth of 2 m. In a recent paper Hendricks and Carter (He81) calculate the flux density of neutrons inside an iron block for incoming neutrons between 2 an 40 MeV energy by means of a Monte-Carlo technique without energy cut-off. They show that in a depth of 1 to 2 m the flux density of neutrons with energies between 1 to 100 keV is 5 to 6 orders-of-magnitude higher than that of neutrons above 1 MeV. The Moyer model cannot be applied to a transverse iron shielding with a thickness which may occur in practice (0.2 - 2 m).

Experimental values for the dose-equivalent attenuation in iron (including all low-energy neutrons) are not published. The usual threshold counters all have too high thresholds. Suitable are calculations taking into account also neutrons with very low energies. Such calculations were performed many years ago by Alsmiller and Barish (Al73). They used a value of 140 g/cm^2 for the mean free path for nonelastic collisions at 250 MeV, but the resulting dose-equivalent attenuation can roughly be described between 40 and 180 cm by an exponential function with a coefficient of 240 g/cm^2. Hendricks and Carter find 210 g/cm^2 for a parallel neutron beam. (The coefficient λ for such a geometry can be used approximately in the expression $\exp(-\lambda d)/r^2$ for a point source). Experimental results with ^{12}C-detectors (threshold 20 MeV) scatter around 180 g/cm^2 (Dubna Ko63, Brookhaven Be74, KEK Ba80). For a rough estimate of the dose equivalent behind a transverse iron shield therefore a value of 200 g/cm^2 seems to be appropriate. Since this value is thought as taking into account the build-up of low-energy neutrons it could be used together with an averaged source term from the table above.

References

Al 73 Alsmiller R. G. and Barish J., 1973, "Shielding against the neutrons produced when 400 MeV electrons are incident on a thick copper target", Particle Accelerators 5, 155.

Ba 80 Ban S., Hirayama, H., Kondo K., Miura S., Hozumi K., Taino M., Yamamoto A., Hirabayashi H. and Katoh K., 1980, "Measurement of transverse attenuation lengths for paraffin, heavy concrete and iron around an external target for 12 GeV protons", Nucl. Instr. Meth. 174, 271.

Be 74 Bennet G. W., Levine G. S., Foelsche H. W. and Toohig T.E., 1974, "Flux distribution in a steel side shield", Nucl. Instr. Meth. 118, 149.

Ca 67 Casey W. R., Distenfeld C.H., Levine G. S., Moore W. H. and Smith L. W., 1967, "Sand as a side shield for 30 GeV protons stopping in the AGS", Nucl. Instr. Meth. 55, 253

He 81 Hendricks J. S. and Carter L. L, 1981, "Computional benchmark for neutrons penetration in iron", Nucl.Sci. Eng. 77, 71.

Ko 63 Komochkov M. M. and Sychev B. S., 1963, "Attenuation of the high-energy neutron flux in a shielding", Atomnaya Energija 15, 325.

Le 72 Levine G. S., Squier D. M., Spapleton G. B., Stevenson G. R., Goebel K. and Ranft J., 1972, "The angular dependence of dose and hadron yields from targets in 8 GeV/c and 24 GeV/c extracted proton beams", Part. Accelerators 3, 91.

OB 68 O'Brien K., 1968, "Tables for the determination of the lateral shielding requirements of high-energy accelerators", HASL-203, Health and Safety Laboratory, U. S. AEC, New York.

OB 69 O'Brien K., 1969, "A solution to the transverse shielding problem for high-energy electron and proton accelerators", 2. Intern. Conf. on Accelerator Dosimetry and Experience, Stanford Linear Accelerator Center.

Ro 76 Routti J. T. and Thomas R. H., 1969, "Moyer integrals for estimating shielding of high-energy accelerators", Nucl. Instr. Meth. 76, 157.

St 81 Stevenson G. R., Kuei-Lin L. and Thomas R. H., 1981, "Determination of transverse shielding for proton accelerators using the Moyer model", LBL 11337, Lawrence Berkely Laboratory, Univ. of California (to be published in Health Physics).

Sy 66 Sychev B. S., Mel'kov V. V., Komochkov M. M. and Zaitsev L. N. 1966, "The transmission of high-energy neutrons in iron-water mixtures", Sov. At. Energy 20, 361