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NEUTRON INTERACTIONS IN SCINTILLATING-FIBER CENTRAL TRACKERS FOR SDC AND D-ZERO

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ABSTRACT

This note investigates the interaction of albedo neutrons with the polystyrene fibers of the scintillating-fiber central trackers proposed by the Fiber Tracking Group for SDC and D-zero. The neutrons are well approximated by a homogeneous, isotropic "gas" whose energy spectrum peaks at 1 MeV. Their predominant interaction is elastic scattering, resulting in recoil protons and ^{12}C nuclei whose maximum ranges are 1.5×10^{-3} cm and 3×10^{-5} cm, respectively. The total interaction probability in a 800-μm-diameter fiber is 4.1%. For the SDC design, at $\mathcal{L} = 10^{33}$ $cm^{-2}s^{-1}$, the interaction rate in a 4-m-long fiber is estimated to be 65 kHz with no calorimeter liner, and 6.5 kHz with a 10-cm-thick polyethylene liner. For 2.7-m-long fibers in D-zero, at $\mathcal{L} = 6\times10^{31}$ $cm^{-2}s^{-1}$, the rate is 15 kHz (no liner). The light output of proton and carbon recoils is estimated to be 1.5 and 0.2 times as large, respectively, as that produced by minimum-ionizing particles. Thus, carbon recoils may not be detected, in which case the neutron counting rates will be 58% of the corresponding interaction rates.

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$cm^{-2}\ yr^{-1}$ at a Tevatron main injector luminosity of $6x10^{31}\ cm^{-2}s^{-1}$. The corresponding per-second rates, obtained from $F' = F/(3.16x10^7\ s/yr)$, are listed in Table I for convenience.

The 1 MeV neutrons entering the fibers interact primarily via elastic collisions with the hydrogen and carbon nuclei that constitute the polystyrene fiber core. At moderate neutron energies -- below 10 MeV for (n,p) collisions -- the scattering is isotropic, and the kinetic-energy spectra of the recoil nuclei are constant from zero up to the maximum possible energy transfer.[6] The kinetic energy of a nucleus of atomic weight A recoiling at an angle α relative to an incoming neutron of kinetic energy K_n is easily shown to be

$$K_A = \frac{4\ A\ K_n\ \cos^2\alpha}{(1+A)^2} \quad .$$

Thus, for $K_n = 1$ MeV the maximum energies of the recoiling hydrogen and carbon nuclei are 1 MeV and 0.28 MeV, respectively.

The probability of a neutron interacting after traveling a distance t in a fiber is $p(t) = 1 - \exp(-\mu t)$, where μ is the linear interaction coefficient. For a small μt this becomes

$$p(t) \approx \mu t \quad . \tag{1}$$

Assuming that the scattering from the polystyrene constituents is incoherent,

$$\mu = \frac{\rho N_o}{W}\ (N_p\sigma_p + N_C\sigma_C) \quad . \tag{2}$$

Here, $\rho = 1.03\ g/cm^3$ is the scintillator density, N_o is Avogadro's number, $W = 104$ is the polystyrene unit-cell ($CH(C_6H_5)CH_2$) molecular weight, $N_p = 8$ is the number of protons per unit cell, σ_p is the (n,p) cross section, $N_C = 8$ is the number of carbon nuclei per unit cell, and σ_C is the $(n,{}^{12}C)$ cross section. For estimation, the cross-section values at the midpoints of the recoil energy distributions are used, so that σ_p (0.5 MeV) = 6.2 barns, and σ_C (0.14 MeV) = 4.4 barns.[7] Equation (3) then gives

for the SDC and D-zero detectors for maximum scintillating fiber lengths of 4.0 m and 2.7 m, respectively, are given in Table I.

TABLE I. Fiber rates due to albedo neutrons.

Detector	SDC $\mathcal{L} = 10^{33} cm^{-2}s^{-1}$		D-zero $\mathcal{L} = 6x10^{31} cm^{-2}s^{-1}$
Max. fiber length (m)	4.0		2.7
	without liner	with liner	without liner
Per-second fluence, F' ($cm^{-2}s^{-1}$)	$3.16x10^4$	$3.16x10^3$	$1.08x10^4$
Neutron interactions, R_{int} (kHz)	65	6.5	15

3. Ranges of recoil nuclei

Before estimating the light output resulting from the proton and carbon recoils produced by interacting neutrons, it is interesting to calculate their ranges. Ranges of charged particles are generally normalized to air at STP, and a graph of proton range, r_p^{air} as a function of proton kinetic energy, K_p, may be found in Evans.[8] The range, r_p, in another material can be estimated using the Bragg-Kleeman rule,[9]

$$r_p = \frac{\rho_{air}}{\rho} \sqrt{\frac{A}{A_{air}}}\ r_p^{air} . \tag{9}$$

Here, ρ is the density of the material, $\rho_{air} = 1.226x10^{-3}$ g/cm^3, and A is the atomic weight of the material.

For a compound, A can be expressed as

$$\sqrt{A} = \sum_i f_i \sqrt{A_i} \quad ,$$

linear function of total energy loss. As an example of the former phenomenon, a stopping 1 MeV proton produces the same light as a stopping 0.25 MeV electron[10] thereby reducing the recoil-proton light ratio above by a factor of four, and the correction for heavy ions is about a factor of ten. Using this information, improved estimates for the proton and carbon light ratios are 1.5 and 0.2, respectively.

A more detailed analysis was also made using a graph of electron specific fluorescence, dL/dx, as a function of specific energy loss, dE/dx, given by Birks.[10] This information, together with dE/dx as a function of E for electrons,[11] was used to produce a curve of dL/dE vs. E. The light output of a stopping 0.25 MeV electron -- the same as that of a stopping 1 MeV proton[10] -- was then found from the area under this curve between 0 MeV and 0.25 MeV, or

$$L_p(1\ \text{MeV}) = L_e(0.25\ \text{Mev}) = \int_{0\,\text{MeV}}^{0.25\,\text{MeV}} \frac{dL}{dE}\, dE \quad .$$

This procedure includes both of the correction phenomena described above. The effect of the second is small and, to the precision of the calculation, the same results were obtained:

$$L_p(1\ \text{MeV})/L_{mip} = 1.5 \ ; \ L_C(0.28\ \text{MeV})/L_{mip} = 0.2 \quad .$$

Neither value is troublesome. Indeed, light production from (n,^{12}C) recoils may be so low as not to be detected. In this case, the neutron interaction rates given in Table I should be multiplied by the factor $\sigma_p/(\sigma_p + \sigma_C) = 0.58$ to obtain the corresponding counting rates.

5. Summary

This note has investigated the interaction of albedo neutrons with polystyrene fibers as proposed for the SDC and D-zero central trackers. The predominant interaction is elastic scattering, resulting in recoil protons and ^{12}C nuclei. These particles will stop in the fibers since their maximum ranges

6. Appendix

To calculate the average neutron path length in a fiber of diameter d, choose a coördinate system whose y axis is tangent to the underside of the fiber and whose z axis coincides with the fiber's diameter, as shown in Fig. 1a. Consider the isotropic, unidirectional flux entering an infinitesimal area dA located at the origin. Let OA be a typical track whose length is $t(\theta,\phi)$, where (θ,ϕ) are the spherical polar coördinate angles of the track.

The intersection of the ϕ = const. plane with the fiber is an ellipse which, in the coördinate system (x',z) shown in Fig. 1b, has the form

$$\frac{x'^2}{a^2} + \frac{(z-d/2)^2}{d^2/4} = 1 \quad , \tag{A1}$$

where $a = d/2\cos\phi$. Using $x' = t\sin\theta$ and $z = t\cos\theta$, Eq. (A1) gives

$$t(\theta,\phi) = \frac{d \cdot \cos\theta}{\cos^2\theta + \sin^2\theta\cos^2\phi} \quad . \tag{A2}$$

The average value of the track length is then

$$\begin{aligned} \bar{t} &\equiv \frac{1}{2\pi} \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta \, \sin\theta \, t(\theta,\phi) \quad , \\ &= \frac{d}{2\pi} \lim_{\substack{\theta^* \to \pi/2 \\ \phi^* \to 2\pi}} \int_0^{\theta^*} d\theta \, \sin\theta\cos\theta \int_0^{\phi^*} \frac{d\phi}{\cos^2\theta + \sin^2\theta\cos^2\phi} \quad , \end{aligned} \tag{A3}$$

where the limiting procedure is introduced to avoid undefined expressions when evaluating the integrals at their upper limits.

The ϕ integral is of the form[12]

$$\int \frac{dx}{p^2+q^2\cos^2 x} = \frac{1}{p\sqrt{p^2+q^2}} \tan^{-1}\left[\frac{p\tan x}{\sqrt{p^2+q^2}}\right] ,$$

so that, with $x = \phi$, $p^2 = \cos^2\theta$, and $q^2 = \sin^2\theta$,

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