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Comparison of aluminum and lucite for shielding against 1 GeV protons

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Abstract

Shielding is the only countermeasure currently available for exposure to cosmic radiation during space travel. We compared aluminum (Al) and polymethylmethacrylate (PMMA, or lucite) shields of 20 g/cm^2 thickness using 1 GeV protons accelerated at the NASA Space Radiation Laboratory. The dose rate increased after the shield, and the increase was more pronounced after the Al than the PMMA shield. No significant differences in the induction of chromosomal aberrations were observed in human lymphocytes exposed to the same dose with no shield or behind the Al and PMMA blocks. However, the biological effectiveness per incident proton was increased by the shields. Simulations using the General-Purpose Particle and Heavy-Ion Transport Code System (PHITS) show that the increase in dose is caused by target fragments, and aluminum produces more secondary protons than PMMA. Nevertheless, the spectrum of particles behind the shield is confined within the low-LET region, and the biological effectiveness is consequently similar.

Keywords: Protons; Shielding; Chromosome aberrations; Fragmentation

1. Introduction

Shielding is a major issue for the design of the spacecrafts for interplanetary missions planned in this century. It is well known that light, hydrogen rich materials, such as polyethylene and plastics, are more effective than heavy elements in shielding space radiation (e.g. Wilson et al., 1995; Shavers et al., 2004). In fact, the fragmentation cross section per unit target (T) mass decreases as $A_T^{-1/3}$, while the ionization power increases as Z_T/A_T. Thus, basic physics suggests that hydrogen is the best material for shielding against heavy ions (Miller et al., 2003). However, for very high energy protons, projectile fragmentation is obviously irrelevant, and the energy loss is small even for thick shields. Protons represent about 87% of the cosmic ray flux and the energy spectrum peaks around 1 GeV. It is then interesting to compare different materials for shielding of this very penetrating (range in water around 3.2 m) particles.

In parallel to physics test, it is very important to compare the biological effectiveness of the particle beams with or without shielding. As we did in our previous tests with iron projectiles (Grossi et al., 2004; Durante et al., 2005) we have exposed human peripheral blood lymphocytes to proton beams with and without shielding. We report the comparison of the experimental results and simulations using shields in aluminum and lucite (PMMA) of the same areal density in this paper.

2. Materials and methods

2.1. Beam and dosimetry

A proton beam at 980 MeV was accelerated at the NASA Space Radiation Laboratory (NSRL), Brookhaven National Laboratory, USA. The LET in water is about

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Table 1
Aberrations scored in human lymphocytes exposed to protons with or without shielding blocks

Samples	Dose (cGy)	Cells analyzed	Aberrant cells	Simple exchanges	Complex exchanges	Fragments
No shield	0	3258	12	7	0	5
	50	651	37	21	3	20
	75	1293	134	64	9	73
	100	452	38	16	11	15
	150	656	119	85	18	103
	200	272	58	41	4	22
	250	553	187	134	50	184
	300	198	66	53	13	21
	350	517	274	226	52	278
Aluminum shield	50	446	25	10	2	13
	100	527	51	32	6	19
	200	204	52	34	6	21
	300	336	108	71	16	48
PMMA shield	50	462	46	16	3	31
	100	266	31	19	0	16
	200	374	77	44	9	38
	300	200	67	53	10	20

0.22 keV/μm. The size of the beam was about 15 cm × 15 cm and the disuniformity in this area below 5%. Three parallel-plate ionization chambers were used as beam monitors, and the dose in different position was measured by a Far West thimble chamber (“egg” chamber). Dose was measured in three different configurations: (i) unshielded beam; (ii) in front and behind a lucite (PMMA, 1.16 g/cm^3) shield of 193 mm thickness; (iii) in front and behind an aluminium (2.7 g/cm^3) shield of 79 mm thickness. For the aluminium block, the dose was also measured at different distances z from the target block along the beam central axis. The beam and its interactions with the targets were simulated using the General-Purpose Particle and Heavy-Ion Transport code System (PHITS), a Monte Carlo code widely used for simulations of high-energy charged particle transport in matter (Sato et al., 2005).

2.2. Biology

The quality factor of the beam with or without shielding has been measured in terms of cytogenetic damage in

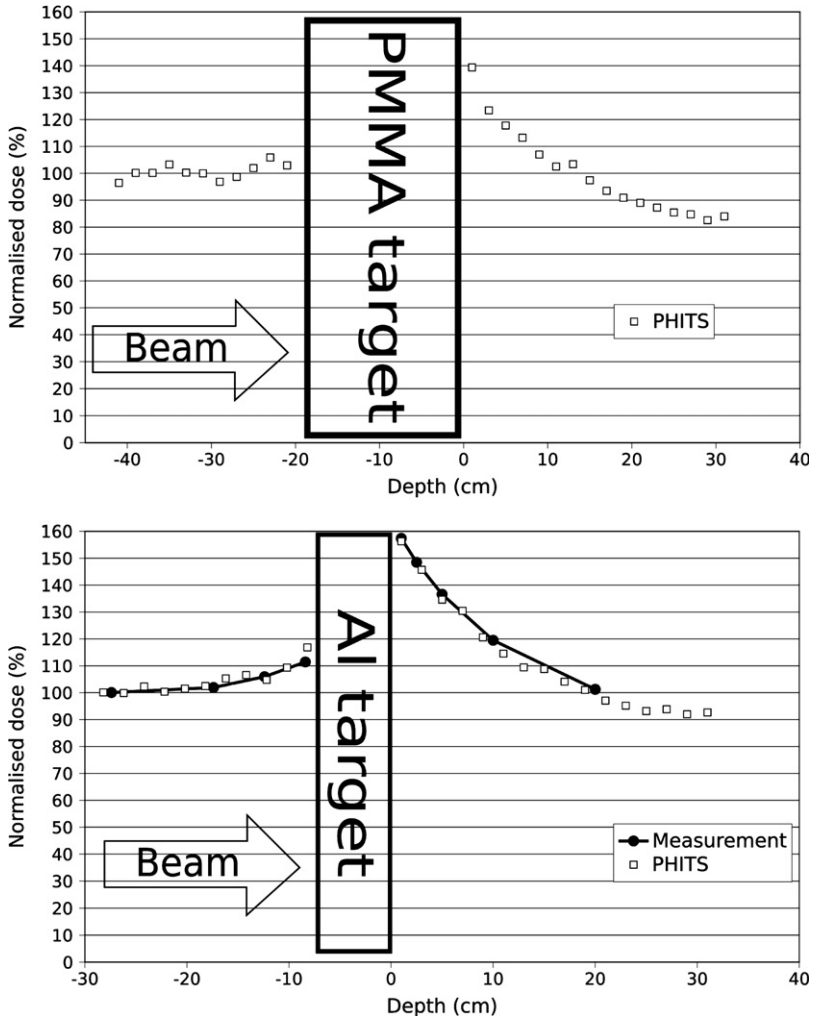

Fig. 1. Dose calculated by PHITS as a function of the distance along the 1 GeV proton beam axis z in the presence of a 20 g/cm^2 Al or PMMA targets. The dose is normalized to the value at $z = -30$ cm. For the Al shield, measured dose values are also reported (closed symbols). Regions before and after the shields are in air.

human peripheral blood lymphocytes as described previously (Durante et al., 2005). Briefly, whole-blood from a male healthy donor was exposed to the beam in the dose range 0.5–3 Gy at a dose rate around 1 Gy/min. Lymphocyte chromosomes were prematurely condensed following 48-h culture using calyculin A. Slides were FISH-painted using whole-chromosome DNA probes (MetaSystems, Altlussheim, Germany) specific for human chromosome 1 (spectrum green) and chromosome 2 (spectrum orange). These two largest human chromosomes cover approximately 16% of the human genome. Coded slides were visualized at a computerized Zeiss epi-fluorescent microscope driven by the Metafer4 metaphase finder and image acquisition system. All kinds of different aberrations in the prematurely condensed chromosomes (PPC) 1 and 2 were classified separately (see Table 1). The experiment was repeated twice.

3. Results and discussion

The dose-rate measured in the sample position was increased by the shielding. In fact, the dose at the sample position (at a few cm from the block) increased about 25% and 40% when the sample was filtered with the blocks in PMMA and Al of the same mass thickness (about 20 g/cm^2), respectively, although we calculated that the LET of the proton beam is increased only about 2% by Coulomb slow-down in both shields.

The PHITS simulations shown in Fig. 1 reproduce very accurately the experimental values and the enhanced ability of Al in increasing the dose behind the shield. As we have shown in our previous paper (Bertucci et al., 2007), the simulation indicates that protons account for over 90% of the measured dose both in front and behind the shield. The remaining fraction is attributed to pions, muons, electrons (from γ-rays) and hadrons, including neutrons. The simulation shows that secondary protons, emitted from the target, are mostly responsible for the observed increase in dose both in front and behind the shield. Fig. 2 shows the proton energy spectra behind the shield in Al or PMMA. PHITS can distinguish the accelerated protons in the primary beam (dashed lines) from secondary protons coming from nuclear interactions between the projectile and the target (dotted lines). Secondary protons at high energy (knock-out protons) are only emitted in the forward direction, while slow (evaporation) protons are emitted almost isotropically, and contribute to the observed increase in dose (>100%) in front of the shield block. The simulation

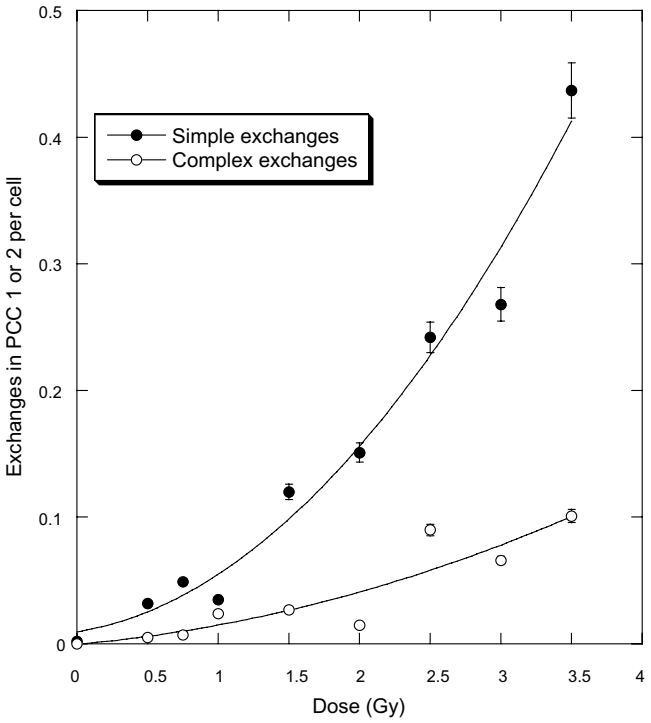

Fig. 3. Chromosomal exchanges in PCC 1 and 2 from human lymphocytes exposed 1 GeV H-beam. Exchanges are divided in simple- and complex-type. The curves are linear-quadratic fits to the data points. Bars are standard errors of the mean values.

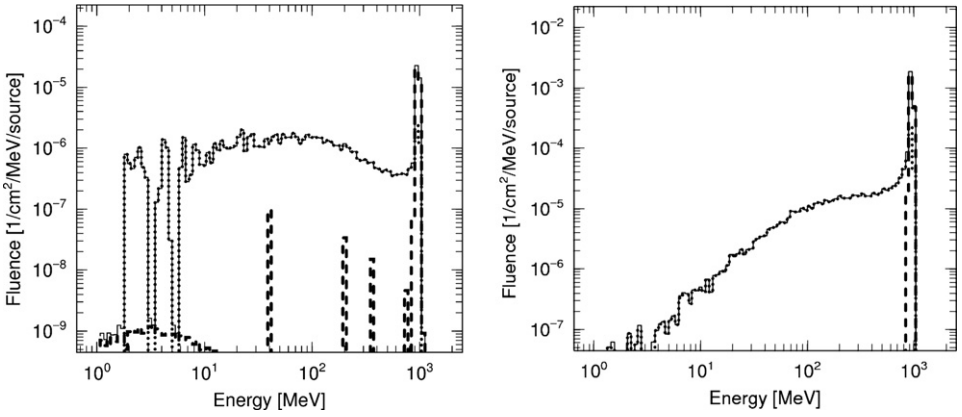

Fig. 2. Proton energy spectra after the Al (left) or PMMA (right) shields, in the sample position ($z = +1$ cm from the shield). The dashed line refer to the incident, primary protons, that had no nuclear interactions with the target. Energy of these protons peaks at 1 GeV in the simulation. The dotted curve is for secondary protons emitted by nuclear reactions in the target.

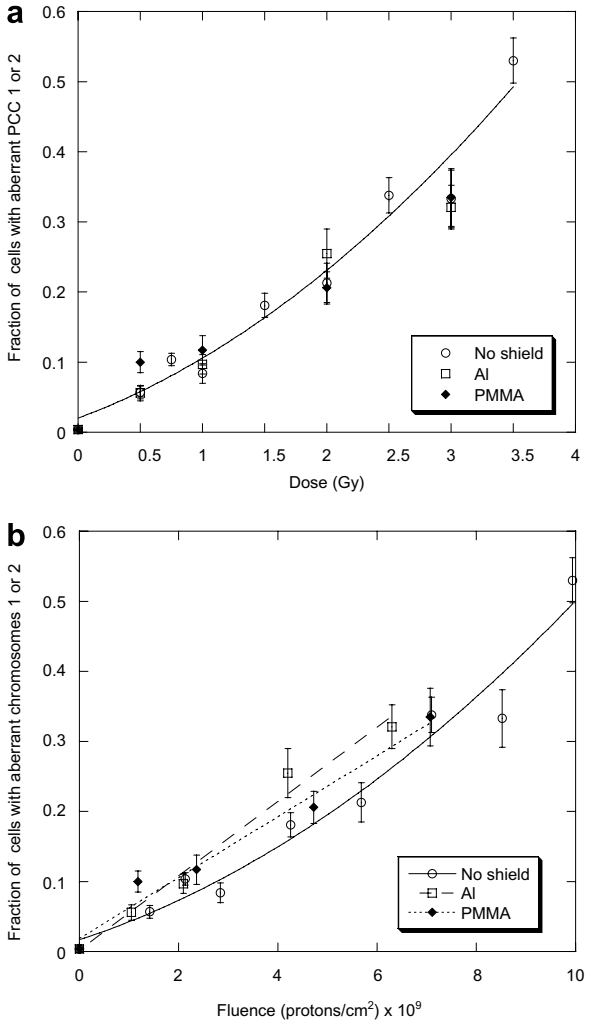

Fig. 4. Chromosomal aberrations in human lymphocytes exposed to the high-energy H-beam with or without shielding. The fraction of lymphocytes with aberrations in PCC 1 or 2 is plotted vs. (a) dose at the sample position or (b) fluence of protons incident on the shield. The curve in (a) is a linear-quadratic fit to the pooled data. Curves in (b) are linear-quadratic fits to the three datasets. Bars are standard errors of the mean values.

shows that Al produces more secondary protons than PMMA.

Data on chromosomal aberrations observed in human lymphocytes exposed to protons are summarized in Table 1. Chromosomal interchanges (dicentrics and translocations) were the most frequent aberration observed in PCC 1 and 2 from irradiated lymphocytes. The frequency of simple- and complex-type exchanges in PCC 1 and 2 are plotted vs. dose of 1 GeV protons in Fig. 3. The fraction of human lymphocytes with aberrant PCC 1 or 2 is shown in Fig. 4 as a function of either dose or fluence of primary protons incident on the shield. No significant difference is observed between shielded and unshielded protons as a function of the dose (Fig. 4a). Because the dose per incident particle is increased by shielding (Fig. 1), chromosomal exchanges per incident protons are also increased when the biological sample is shielded by PMMA or Al thick blocks (Fig. 4b).

The biological data suggest that the radiation field behind the shield is not more effective than the primary beam at the same dose. The LET spectra in the position of the blood sample, as simulated by PHITS, are shown in Fig. 5. The great majority of the secondary protons have LET below 1 keV/μm, especially for PMMA. The beam behind the shield is then still characterized by a low-LET, both of Al and PMMA, thus explaining the lack of difference in the measured biological effectiveness at the same dose.

The results presented here indicate that shielding increases the dose per incident 1 GeV proton, and the increase is more pronounced for Al than PMMA, because the heavy materials produce more target fragments. The biological effectiveness per unit dose is not significantly changed neither by aluminum nor by lucite, because the LET spectrum remains in the low-LET region. We conclude that for relativistic protons, as for heavy ions, light materials can be preferable to high-Z elements, because they produce less secondary radiation.

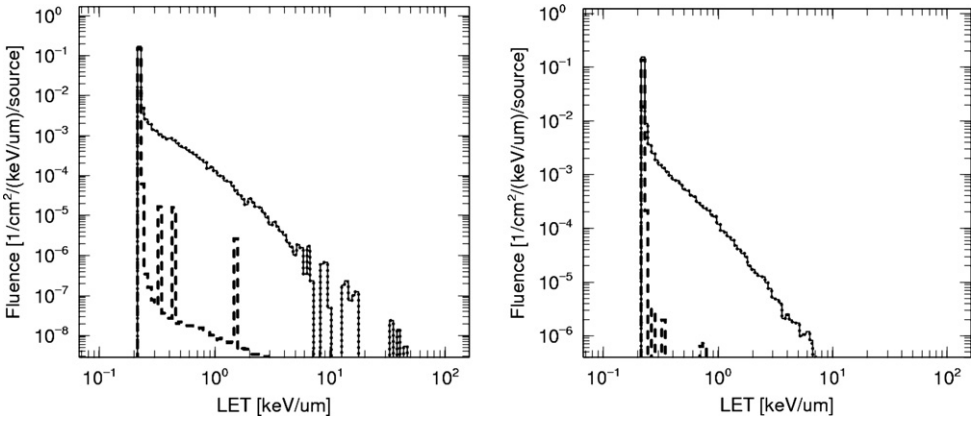

Fig. 5. LET spectrum simulated by PHITS after the Al (left) or PMMA (right) shields, in the sample position ($z = +1$ cm from the target). The dashed line refer to the incident, primary protons, that had no nuclear interactions with the target. LET of these protons peaks at 0.22 keV/μm in the simulation, corresponding to 1 GeV in water. The dotted curve is for secondary protons emitted by nuclear reactions in the target.

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