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Review

Shielding of Cosmic Radiation by Fibrous Materials

Tomasz Blachowicz [1] and Andrea Ehrmann [2,*]

1 Institute of Physics—Center for Science and Education, Silesian University of Technology, 44-100 Gliwice, Poland; tomasz.blachowicz@polsl.pl
2 Faculty of Engineering and Mathematics, Bielefeld University of Applied Sciences, 33619 Bielefeld, Germany
* Correspondence: andrea.ehrmann@fh-bielefeld.de

Abstract: Cosmic radiation belongs to the challenges engineers have to deal with when further developing space travel. Besides the severe risks for humans due to high-energy particles or waves, the impact of cosmic radiation on electronics and diverse materials cannot be neglected, even in microsatellites or other unmanned spacecraft. Here, we explain the different particles or waves found in cosmic radiation and their potential impact on biological and inanimate matter. We give an overview of fiber-based shielding materials, mostly applied in the form of composites, and explain why these materials can help shielding spaceships or satellites from cosmic radiation.

Keywords: cosmic rays; high energy interactions; space radiation; radiation protection; long-term space travel

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1. Cosmic Radiation

Cosmic radiation has been investigated for decades. The origin of cosmic radiation was first found to be interstellar space [1] with wholly or partly ionized gas moving in magnetic fields [2], accelerated by electromagnetic fields (e.g., surrounding the sun) [3]. With new experimental approaches, more insights can be gained into cosmic rays stemming from the sun, of galactic or extra-galactic origin [4]. Nevertheless, the possible sources of cosmic radiation have still been under discussion during the past decade [5–7].

Cosmic radiation is nowadays subdivided into high-energy particles stemming from the sun, mostly protons, which are especially emitted in solar eruptions, and high-energy particles stemming from the solar system or from outside of it. The so-called primary cosmic rays, which are produced directly through processes in space, mostly consist of protons (~89%), alpha particles (~9%), and other bare nuclei of atoms (~1%), as well as a few solitary electrons (i.e., beta particles, ~1%), that is, positively or negatively charged particles with particle rest masses mostly in the range of 938 MeV/c^2 (proton) to 3727 MeV/c^2 (alpha particle); while the secondary cosmic rays, produced by collisions of primary cosmic rays with the atmosphere or with spacecraft or tissue, include many more different particles, such as muons, pions, neutrinos, and neutrons, but also protons and alpha particles, as well as X-rays [8]. The energy spectrum of all cosmic-ray particles is shown in Figure 1 for higher energies, as measured by different experiments [9]. Usually, energies up to 10^{20} eV/particle can be expected, with the largest particle flux at lower energies and a maximum around 10^2–10^3 MeV/nucleon [8]. Cosmic rays with high atomic number and energy, also called HZE (High Z and Energy) ions, make up only approximately 1% of the galactic cosmic rays, but due to their high energy and the high charge of these ions, they are as dangerous as the much more frequently occurring protons [10,11]. While cosmic radiation is deflected by the Earth's magnetic shield so that very high-energy particles only scarcely reach the ground [12], this is naturally not the case during space travel.

The impact of cosmic rays on electronics, especially smaller transistors and other parts of computers, is not even negligible on earth, not to talk about space [13]. This is why many attempts are being made to avoid damage of material, electronics, or even humans by cosmic radiation during space travel by magnetic or material-based shielding. Here we give an overview of material-based shielding, concentrating in particular on the fiber-based solutions since such textile fabrics or composites can combine shielding with favorable mechanical properties and are thus advantageous as compared to die-casted and other forms without textile sub-structures.

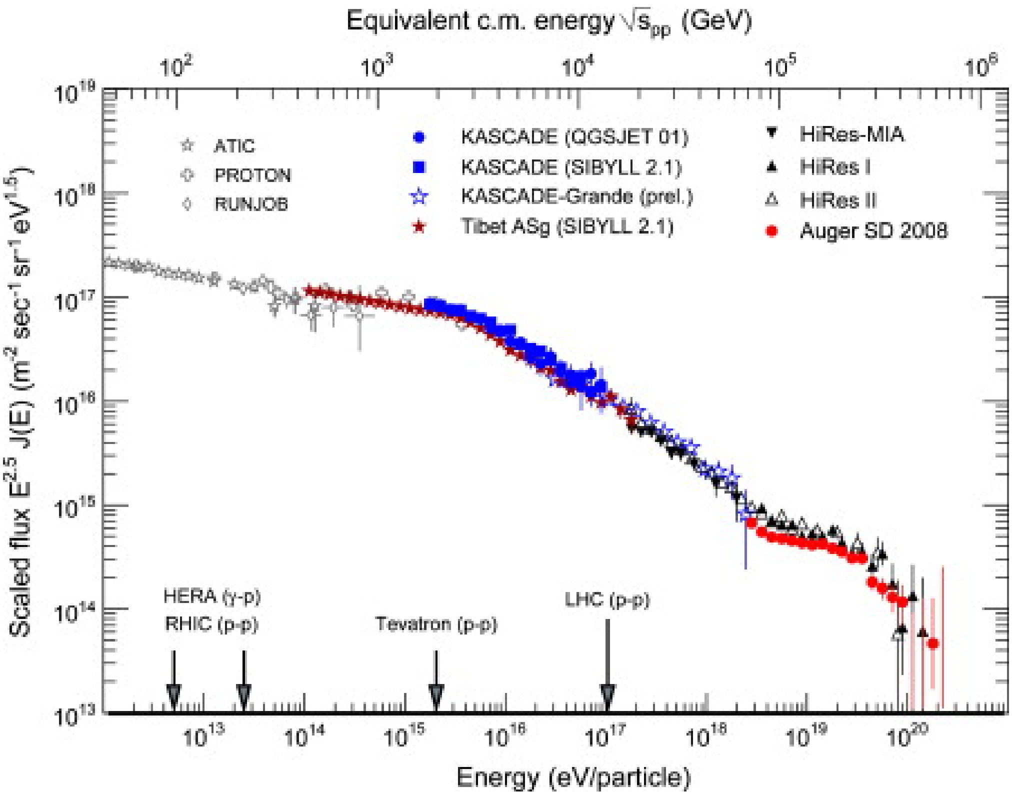

Figure 1. All-particle cosmic-ray energy spectrum as obtained by direct measurements above the atmosphere by the ATIC, PROTON, and RUNJOB, as well as results from air shower experiments, showing Tibet results obtained with SIBYLL 2.1, KASCADE data (interpreted with two hadronic interaction models), preliminary KASCADE-Grande results, and Akeno data. The measurements at high energy are represented by HiRes-MIA, HiRes I and II, and Auger. Reprinted from [9], with permission from Elsevier.

2. Impact of Cosmic Radiation during Space Travel

As mentioned before, the impacts of cosmic radiation on humans, but also on material and electronics used in spacecraft, are manifold. Thus, only a brief overview can be given here about some studies dealing with this topic.

Bouville and Lowder compared the exposure of astronauts to cosmic radiation with the dose equivalents of other humans [14]. They calculated that people staying on the ground receive an annual dose equivalent of approximately 270 µSv in the form of charged particles and about 50 µSv neutrons, while aircraft flight crews receive an additional dose equivalent of approximately 1 mS. Space travelers, however, were calculated to expect a dose equivalent of 0.1–1 Sv or even higher, especially due to unusually large solar flares.

Rodman et al. investigated the impact of simulated cosmic radiation on human hematopoietic stem and progenitor cells [15]. They exposed human hematopoietic stem/progenitor cells to doses of high-energy proton and iron ions, as delivered by an accelerator, and found mutations in genes responsible for hematopoiesis (i.e., formation of blood cellular components) which were different from those caused by γ-radiation. They also mentioned that the common exposure to both protons and iron ions, as expected during space travel, caused more damage than exposure to only one of the particle species.

In experiments with young-adult mice to which single whole-body doses of ^{56}Fe were applied, Miry et al. found dynamic effects on the hippocampus [16]. The consequences remained for 20 months, which the researchers interpreted as a life-long influence on plasticity and cognition, suggesting the exposure to cosmic radiation can durably change brain health and cognitive functions after long-term travel in deep space.

Norbury et al. gave a broad overview of human health risks for different mission scenarios [17]. They pointed out that galactic cosmic ray ions could penetrate tens of centimeters into aluminum or water (i.e., also into the human body), resulting in the fact that complete shielding from space radiation will not be possible, but maximum exposure doses have to be defined instead.

Long-term effects for astronauts have been investigated by different research groups. Krukowski et al. found that proton exposure can result in cognitive loss by modifying neuronal and microglial cell function [18]. Other researchers also reported possible damage of the central nervous system [19,20] and disturbance of muscle movements [21]. Almeida-Porada et al. reported on DNA damage and mutations within human hematopoietic stem cells upon galactic cosmic irradiation [22]. Complex DNA damage, in particular, as can occur due to HZE irradiation, is expected to lead to serious problems since it is more difficult to repair than normal DNA damage [23,24]. Another critical health concern is carcinogenesis, which was examined in diverse animal experiments, showing that HZE particles led to more aggressive forms of cancer [25], while long-term exposure to gamma- or X-rays showed significantly lower risk of carcinogenesis than acute exposure [26].

It must be mentioned, however, that conclusions drawn from laboratory tests cannot always be fully transferred to space travel. Chancellor et al. described the deviations between laboratory research and empirical findings on astronauts, which they ascribed to the complex space environment and the limitations of extrapolating animal models to real humans [27].

The major risks to human health during space travel was defined by NASA as carcinogenesis, bus also degenerative tissue issues, risks to the central nervous system during a mission and afterwards, as well as acute radiation syndromes [28]. These major risks are suggested to be investigated in detail to make future missions to Mars and so on safer [29].

Besides these severe possible impacts on human health, cosmic radiation can also significantly influence electronics in satellites, spacecraft, and so on [30]. Höeffgen et al. mention the problems in testing electronics for simulated cosmic radiation on earth (i.e., with energies up to 10^{20} eV with a flux maximum of 1 GeV per nucleon) [31]. They describe previous simulations of these high energies by fluxes of lower energy to reach the same energy loss in large devices, while nowadays this approach no longer works due to directly neighboring heavy elements and sensitive elements inside miniaturized electronics and due to 3D electronic structures. Thus, they showed data gained with high-energy ion beams and suggested further measurements up to 10 GeV/nucleon, using the most recent electronic devices, complete systems, or even small satellites.

An interesting approach to deal with possible radiation damage due to exposure of electronics to cosmic radiation or also to the high-radiation environments of nuclear reactors or particle accelerators was suggested by Wang and Xiao [32]. They reported that field-effect transistors built from carbon nanotubes as channel material and an ion gel as gate material were found to show high tolerance to such radiation, and if damage occurred due to high-energy radiation, annealing could be used to recover the original state. Alternatively, Kim suggests using nanoscale vacuum transistors based on silicon carbide wafers as a radiation-tolerant alternative to recent electronics, especially for the planned mission to Titan in 2026 [33].

Due to these non-negligible influences of cosmic radiation, especially on humans, but also on electronics in satellites and other unmanned spacecraft, many research groups are investigating possibilities to shield the interior of spacecraft from the broad range of cosmic radiation, especially the high-energy particles. The next section thus gives an overview about the possible materials which may provide sufficient shielding properties.

3. Cosmic-Ray-Shielding Materials

Generally, particles such as protons or neutrons can be shielded by materials containing hydrogen, while photons in the X-ray or gamma-ray range need high-electron-density materials, such as lead.

The challenging problem of shielding cosmic radiation to protect astronauts is the production of secondary particles inside the materials used as shields. Such secondary products of the interaction of cosmic rays are, as mentioned above, neutrons, protons, pions, and other particles influencing human DNA. From that elementary particle perspective, materials built from light atoms like hydrogen and carbon are advantageous (i.e., polymeric materials). This is why, for example, polyethylene-based structures are more effective in protection than alumina or lead, combining high hydrogen content with structural integrity [34]. On the other hand, water is not necessarily an ideal solution since it contains oxygen, which is heavier than carbon.

Spillantini et al. mention in their review about active and passive shielding methods the problem of bulky, heavy shielding [35]. They point out that light, highly hydrogenated materials—especially polyethylene—are thus ideal to perform shielding from cosmic irradiation. Polyethylene belongs to the materials already used in the ISS crew sleeping quarters [36]. Recent radiation shields often contain ultra-high-molecular-weight polyethylene (UHMWPE) due to the combination of good shielding and mechanical properties [37].

Shielding against galactic cosmic radiation, secondary neutrons, and solar energetic particles can generally be performed by materials which contain hydrogen, boron, and nitrogen [38]. In a simulation study by NASA, boron nitride materials containing hydrogen were shown to have superior shielding properties as compared to polyethylene, which is broadly used for this purpose.

Bennington et al. filed a patent for a spacecraft and spacesuit with radiation shields, also based on hydrogen-containing material, stored in a polymer, reaching a higher hydrogen content than polyethylene [39]. They mention hydride or borohydrides as possible forms of hydrogen and suggest electrospinning, casting, or sintering as possible methods to form fibers or solid casts, fulfilling these requirements.

The focus of this review is an overview of recent fiber-based passive shielding materials that offer protection from cosmic radiation, starting with UHMWPE, as one of the most often applied materials, and going further to other polymers, polymer blends, and fibrous nanocomposites, including inorganic material to further support the shielding efficiency.

4. UHMWPE as Fibrous Shielding Material

UHMWPE belongs, as mentioned before, to the recently strongly investigated and already applied materials for shielding humans and instruments from cosmic radiation. UHMWPE is semicrystalline, that is, it consists of amorphous parts with crystalline lamellae embedded. In fibrous form, it can be used to prepare usual textile fabrics by weaving, knitting, or even producing nonwovens [40]. Their high strength and stiffness is reached by extreme stretching during the gel spinning process, resulting in highly aligned polymer chains in the crystalline regions [41]. In this way, a tenacity of approximately 10× the value of steel fibers is reached [42]. While UHMWPE fibers usually suffer from low melting temperatures, drawing with ratios larger than 20 can be used to increase the melting temperature to approximately 150 °C, which is sufficient for many applications [43].

Besides these good mechanical properties, making it also useful to shield spacecraft from space debris [44], UHMWPE is also highly interesting for the shielding of cosmic rays. Typically, composites from a resin in which UHMWPE fibers are embedded are applied for this purpose. However, the fiber–matrix interface in these composites is highly problematic due to the chemically highly inert UHMWPE fibers, often reducing the required shielding as well as the mechanical properties. This is why some groups have investigated possibilities to modify the fiber surface, aiming at a better adhesion, but usually at the cost of reduced mechanical properties [45–48].

The other way is to modify the matrix. In the group of Zhong, the possibility to use a reactive nano-epoxy matrix containing reactive graphitic nanofibers to improve wetting and adhesion to UHMWPE fibers was investigated [49–51]. Using ^{35}Cl ions with 1 GeV/nucleon, they performed radiation tests mimicking the heavy ions of the galactic cosmic ray field and found no negative influence of the additional graphite nanofibers [50].

Similar UHMWPE/nano-epoxy composites were investigated in comparison with hybrid UHMWPE/glass/nano-epoxy as well as pure epoxy as the matrix in radiation tests at the NASA Space Radiation Laboratory at Brookhaven National Laboratory [37]. Here, beams of 1 GeV/nucleon ^{35}Cl were used in the alternating gradient synchrotron accelerator, representing the heavy ion component of galactic cosmic rays. Both UHMWPE/epoxy and UHMWPE/nano-epoxy showed a slightly higher dose reduction than pure polyethylene, while the hybrid composites showed a clear reduction of the radiation shielding properties by more than 25%.

Another new resin was suggested by Iguchi et al., who developed a hydrogen-rich benzoxazine resin, in this way supporting the shielding properties of the pure UHMWPE [52]. For this, they developed different bifunctional benzoxazines from meta-substituted alkoxy phenols and diamines with varying hydrocarbon chain lengths. Using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), they found an influence of the diamine chain length on the reactivity of the developed benzoxazines, with larger chain lengths leading to an increase of the polymerization temperature and decrease of the thermal stability. The optimum resin, depicted in Figure 2 as a monomer, was shown to have much higher shielding properties than epoxy using NASA's On-Line Tool for the Assessment of Radiation in Space (OLTARIS), making this UHMWPE/benzoxazine composite favorable in comparison with common epoxy.

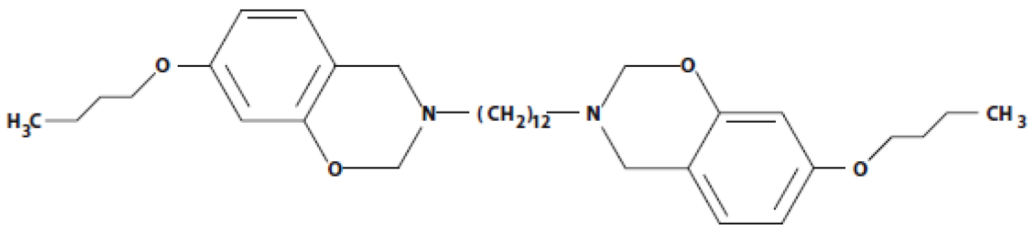

Figure 2. Molecular structure of the optimized 3BOP-daC12 benzoxazine monomer. From [53], originally published under a CC-BY license.

Investigating the optimized benzoxazine polymer in terms of mechanical and shielding properties, they found especially high ultimate tensile strength and tensile modulus at low temperatures of −50 °C, as compared to room temperature [53]. Combined with thin carbon fiber skin layers, the mechanical properties could be further enhanced, however, at the cost of reduced shielding and higher mass. Simulations with OLTARIS [54] showed significantly better shielding properties for all sandwich panels in comparison with aluminum, while the shielding of the whole composite was only 2% lower than the value for pure UHMWPE, making this composite well suited for cosmic shielding.

Cummings et al. concentrated on the effect of proton radiation on pure UHMWPE [55]. They applied proton irradiation at doses of 0–35 Gy at a rate of 0.54 Gy/min using a 155 MeV proton beam to different UHMWPE grades and found changes in different material properties, depending on the UHMWPE grade. These irradiation doses were chosen to simulate cumulative exposure during a ten-to-twenty-year space flight. The authors mention, however, that low doses in particular cause more oxygen to diffuse into the material, which may lead to higher material degradation than high-dose-rate events. Similar experiments were performed by NASA, simulating expected radiation dosages for space suit softgoods during a Mars reference mission as well as equivalent dosages at 2×, 10×, and 20× the predicted dose, and finally a simulated 50-year exposure [56].

Due to the aforementioned advantages of polyethylene materials, and especially UHMWPE, composites including UHMWPE or other polyethylenes can now be regarded as references for lightweight shielding materials [57–59]. Nevertheless, combining UHMWPE with other low-Z materials can be supportive to reduce the aforementioned degradation of polyethylene upon exposure to UV irradiation and high temperature [60]. Such approaches are described in the next sections.

5. Boron, Boron Nitride, and Boron Carbide

While polymers can efficiently reduce the energy of neutrons from cosmic radiation, the resulting low-energy neutrons can react with nuclei in the human body or create errors in electronics. A high absorption of neutrons can be found in materials containing the stable boron isotope ^{10}B, which has a large cross-section to absorb neutrons [61,62]. This is why Ko et al. embedded boron powder or boron carbide whiskers into polyimide samples and found over 90% absorption of the incident neutrons in a sample of 5 mm thickness, tested with a PuBe thermal neutron source, containing 15% amorphous boron powder, without significant changes of the thermal properties [63].

Kowbel et al. applied boron fibers as a method to improve mechanical and shielding properties at the same time [64]. While boron powder can also be used to increase the mechanical properties of a matrix slightly, they found a composite strength higher than 1 GPa for the boron-fiber-reinforced matrix, as compared to values in the order of magnitude of some ten MPa for the pure matrix.

Manzlak et al. embedded boron carbide (enriched $^{10}B_4C$) into polypropylene (PP) fibers, which led to a small reduction in tensile strength and modulus, while a double-layer woven fabric of these filaments with a thickness of 0.8 mm resulted in a reduction of the neutron fluence by 42% [65]. Similarly, Huang et al. embedded boron carbide into a carbon-fiber-reinforced composite and found not only improved thermal and mechanical stability due to the boron carbide filler, but also good neutron shielding, as measured by an Am-Be neutron source and detected by a lithium glass scintillator [66].

Another often used material is boron-nitride (BN). BN belongs, in the form of fibers or nanotubes, to the materials with high absorption capacity for electromagnetic radiation [67,68]. An advantage of this material is that boron nitride is generally suggested by NASA as fibrous reinforcement for spacesuits and so on [69]. Such BN multi-walled nanotubes can be produced with inner diameters of a few nanometers and lengths of a few hundred nanometers [70].

Kang et al. investigated the neutron cross-section of a polyimide matrix with and without 2 wt% of BN nanotubes and found an increase of 120% upon the addition of the BN nanotubes [71]. These experiments were carried out by neutron activation analysis, leaving indium foils exposed overnight to ensure saturation of the activation, and afterwards comparing the time-dependent activity after activation with and without shielding materials. These decay curves for foils exposed with or without different shielding materials could be used to calculate the thermal neutron absorption cross-sections of the samples under investigation.

Polyethylene-based thermoplastic composites reinforced with boron nitride were investigated by Herrman et al. [72]. They embedded BN in injection-molding-grade high-density polyethylene and also tested the samples by neutron exposure of an indium foil with thermal neutrons (<0.5 MeV), with or without shielding of the foil by the BN-composites. The mass absorption cross-section was calculated from the average initial activity of the indium foils. They found a reduced initial radiation activity of the foil, that is, an increased mass absorption, with increasing amount of BN (Figure 3).

Mani et al. used another approach and combined boron and boron carbide nanoparticles as well as gadolinium nanoparticles with UHMWPE/epoxy composites [73]. Producing sandwich panels by vacuum-assisted resin transfer molding, they found more than 99% shielding of these composites against neutron irradiation, while the core materials maintained their mechanical and thermo-physical properties after the radiation experiments. Introducing the same nanoparticles into high-molecular-weight polyethylene/epoxy composites resulted in more than 99% shielding performance for all sandwich panels, with boron nanopowder showing the highest radiation-shielding efficiency, as tested with thermalized neutrons and measured by the transmitting neutron flow through the sample [74,75]. With a similar technique, Ghazizadeh et al. prepared composites from carbon-fiber-reinforced epoxy composites with or without BN nanoparticles and found a positive impact on the mechanical properties of the composites even for small amounts of BN nanoparticles [76].

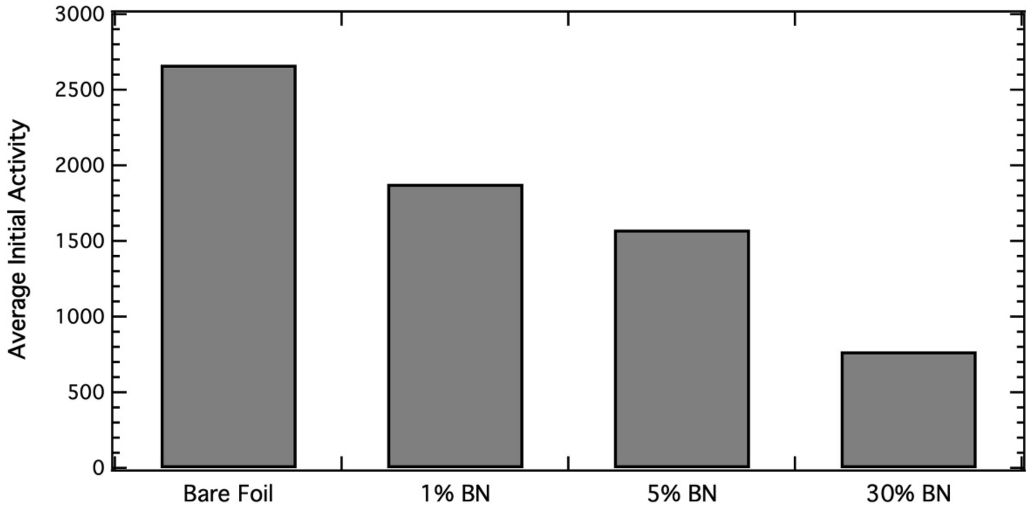

Figure 3. Average initial radiation activity. Reprinted from [72], with permission from Elsevier.

As these examples show, boron can be used in a broad variety of compounds and shapes to be embedded in fibers or matrices, especially for shielding of thermal neutrons. There are, however, more materials which can be used in fibrous shape or in combination with different fibrous materials to shield cosmic radiation.

6. Carbon Fibers

Besides polyethylene, carbon materials can also be used to provide shielding from cosmic radiation. Cohen reported on a full-carbon shield which was tested by bombardment with iron nuclei at 1 GeV/nucleon and showed the second-best dose reduction after polyethylene, before aluminum and lead [77]. Interestingly, the carbon sheet even showed a better overall reduction in radiobiological damage to a lymphocyte cell culture, which was the target of the iron nuclei beam.

Similarly, Wu et al. simulated shielding against 1 GeV/nucleon ^{56}Fe as a typical representative of high-energy galactic cosmic rays, using the Geant4 radiation transport code [78]. They again found PE to show the best shielding efficiency for a given areal density, followed by water, carbon fibers, and aluminum.

Combining graphite fibers with polyethylene (PE), Emmanuel and Raghavan investigated the possibility of preparing optimized shields for highly elliptical orbit satellites [79]. While pure graphite alone has better shielding properties than the often used aluminum, its mechanical properties are insufficient, resulting in the necessity to improve them by adding materials with higher atomic number. They found that, ideally, PE as the low-Z material in this composite should be at the surface layer and interact firstly with the incident radiation, in this way enabling the building of a multi-layer composite from PE and graphite which gives better radiation shielding, as simulated with a particle transport simulation code, taking into account solar particles, cosmic rays, protons, and electrons along the highly elliptical orbit. A three-layer shield from UHMWPE and graphite fibers was also patented, however, with the first layer containing UHMWPE and graphite, the second only polyethylene, and the third a ceramic material [80].

A large simulation comparing the shielding properties of 18 single-element materials and 10 recently used astronautic structural materials against high-energy protons found the elements with low atomic number to be ideally suited, as well as fiber-reinforced polymers, such as carbon-fiber-reinforced polymers [81].

Besides these simulation-based suggestions, Stehlikova et al. report in-orbit measurements of different carbon-fiber composites, performed in the CubeSat VZLUSAT-1 [82]. The shielding material contains carbon fiber meshes and light elements in the resin. They found a more or less energy-independent shielding for the tungsten reference shield, while the carbon composite shows higher shielding for lower energy (up to 20 keV) of the incident rays and lower values for higher energies. Nevertheless, they mentioned that the areal mass of the carbon shield is one order of magnitude lower than that of the tungsten shield.

Different types of high-energy radiation from a ^{210}Pb source (X-rays, gamma-rays, and high-energy electrons with energy 1.16 MeV) were used to investigate the shielding properties in vacuum of different pitch-based graphite fiber composites, materials which may one day replace the usual aluminum structures in spacecraft [83]. For ionizing radiation, pure graphite epoxy composites were found to have only 40% of the aluminum mass absorption. Bromine intercalation, however, significantly increased this result to 170% of the mass absorption coefficient of aluminum, and iodine monobromide intercalation even led to 300% of the aluminum mass absorption coefficient, showing the large changes connected with intercalation. Shielding against β particles, on the other hand, was nearly identical for all materials under examination.

Besides purely experimental and purely simulating investigations, Sihver et al. correlated both by simulating with the 3D Monte Carlo Particle and Heavy-Ion Transport code System (PHITS) and measuring with the anthropomorphic phantom "Matroshka", mimicking a human head and torso and equipped with 6000 radiation detectors, which is located on the ISS [84]. They found very good agreement between simulated and measured radiation doses, in spite of a simplified model of the shielding of the ISS, with the simulations slightly overestimating the radiation doses.

7. X-ray Shielding

While shielding of cosmic radiation is mostly related to heavy-ion radiation, there is also a certain amount of X-ray irradiation [85], which can produce oxidative DNA damage by free radicals or other damage to humans in space [86]. While medical personnel and patients are usually protected from X-ray irradiation by lead aprons, these are not only quite heavy and prone to structural damage [87], and lead is also highly toxic, in this way possibly causing health risks [88].

This is why polymeric composites are also investigated in the medical sector, such as PE, UHMWPE, epoxy, and so on, combined with small metallic particles, such as tungsten or bismuth, but also gadolinium, zirconium, or barium [89–92]. It must be mentioned that, completely oppositely to the aforementioned choice of light elements for shielding from heavy nuclei and other high-energy particles, heavy elements are necessary here. Thinking about X-rays in cosmic radiation, it is especially interesting to investigate tantalum or tungsten, which are already used in Z-graded materials for shielding of cosmic radiation [93,94].

Another material combination was suggested by Li et al., who investigated a basalt-fiber-reinforced epoxy matrix with erbium oxide (Er_2O_3) [95]. This composite was tested in terms of shielding against X-ray and γ-radiation from 31 keV to 662 keV, as shown in Figure 4. For relatively low energies up to 80 keV, they found a much larger mass attenuation coefficient of the composite than of aluminum, while shielding of X-ray and gamma ray radiation by the composite was generally high.

Kim and Son used polyethylene terephthalate (PET) fibers with $BaSO_4$ as well as a tungsten double-layered composite yarn to prepare lightweight shielding clothes for flight attendants and showed by tests with a medical X-ray-generating device that these materials were suitable for low-dose shielding for aviation crews who are affected by cosmic radiation when flying [96].

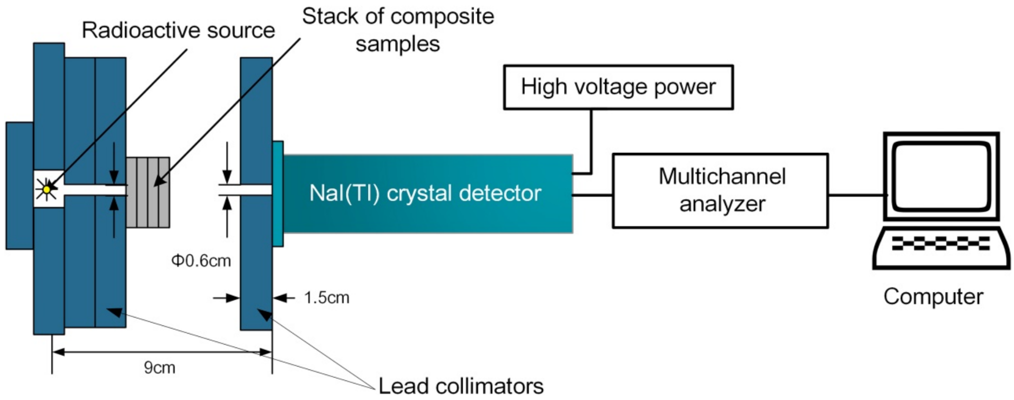

Figure 4. Investigation of photon-shielding properties. Reprinted from [95], with permission from Elsevier.

Combining cellulose fibers with a high amount of inorganic X-ray absorbers, such as barium sulphate, barium titanate, or bismuth oxide, Günther et al. found high X-ray absorption properties in the energy range of 4–14 keV, as detected in a reflection geometry with the textile fabric placed on a copper disk, and direct X-ray transmission to enable measurements up to 40 keV [97]. Similar to the previously mentioned study, here the aim was not to prepare composites, but normal wearable clothes which can be used as additional protective devices against X-ray and possibly other electromagnetic radiation in combination with thicker structural materials in the walls of a spacecraft [98].

The combination of cellulose nanofibers and bismuth nanoparticles was also embedded into a polymer matrix [99]. Comparing this constellation with bismuth microparticles, Li et al. found that only $\frac{1}{4}$ of the bismuth mass was necessary to reach the same shielding against X-rays when nanoparticles were used instead of microparticles, which they attributed to the even distribution of the nanoparticles inside the polymer matrix.

Besides cellulose, other natural fibers are used for X-ray shielding. Impregnating La_2O_3 and Bi_2O_3 nanoparticles into natural leather resulted in X-ray-shielding properties of 65–100% for an energy range of 20–120 keV [100]. Similarly, X-ray attenuation of more than 90% in the energy range below 50 keV and 65% at 83 keV, measured in transmission, were reached by embedding bismuth and iodine into natural leather, while simultaneously, the mechanical properties as well as water vapor permeability were significantly improved as compared to a lead apron [101]. Bi/Ce-natural leather composites were found to have nearly 100% X-ray shielding for energies below 40 keV and up to around 70% shielding for energies of 120 keV, as evaluated by an X-ray mono-energy generator and measured after the shielding material by an ionization chamber [102]. Quan et al. again investigated a lower energy range up to 50 keV, where they found UHMWPE/polyester/CeO_2 composites well suited for shielding against X-ray, measured in transmission, combined with high mechanical strength, and air and water vapor permeability [103]. Shielding of higher-energy electromagnetic radiation—that is, gamma radiation—by fibrous materials is only scarcely reported in recent scientific literature [95,104]; more often, the influence of gamma rays on the oxidation of UHMWPE and other fibrous materials was studied [59].

8. Other Materials for Shielding of Cosmic Radiation

While natural fibers were previously mentioned in terms of shielding of X-rays, Sitepu et al. investigated palm fibers and palm shell as a possible material for shielding of thermal neutron radiation using gold foil activation, that is, activating gold foils glued to the shielding sample by irradiation for 15 h and afterwards determining the activity of the gold foil, which is proportional to the neutron flux trough the sample [105]. This possibility was attributed to the high amount of carbon in palm fibers and shells, that is, more than 70%.

Besides the aforementioned polyethylene, other polymers were investigated by different research groups. Lobascio et al. found good shielding of Kevlar and Nextel fibers against heavy-ion cosmic radiation, as tested with 1 GeV/nucleus iron or titanium ions in an accelerator, with Kevlar, being rich in carbon atoms, showing an efficiency near to polyethylene and a high reduction of chromosomal damage [106], as was also reported for pure carbon sheets [77].

Different polymers, such as polyetherimide and polysulfone, as well as lithium hydride, water, graphite nanofibers, polyethylene, and aluminum oxide as usual references, were simulated by Borggräfe et al., taking into account the radiation during a manned Mars mission [107]. They found that besides an aluminum shield, materials with predominant hydrogen content must be used to reduce the secondary particle production. Besides PE shielding, using water tanks as shields, surrounding the crew quarters, was also suggested.

9. Discussion

While the amount of experiments and simulations dealing with shielding humans and electronics from the different components of cosmic radiation is high, many of them are based on foils or plates, with relatively few fibrous solutions. UHMWPE-based shields are mostly fiber-based since this material gets its high strength due to stretching; however, shielding composites often contain nanoparticles instead of micro- or nanofibers.

This result of our literature survey is unexpected, since many of the relevant shielding materials can be produced in the form of fibers, which usually improves their mechanical properties. On the other hand, some studies mention a highly homogeneous dispersion of shielding nanofillers as a prerequisite to reach good shielding properties, making the use of foils or sheets possibly advantageous as compared to anisotropic woven fabrics or other fibrous structures.

A special technique to produce fibers, which was only very scarcely found in the literature, is electrospinning [108–110]. By producing poly (vinyl alcohol) (PVA)-based nanofibers with Bi_2O_3 or WO_3, Jamil et al. prepared nanofiber mats which were suggested to block X-ray photons [111]. Experimental studies dealing with electrospun materials for shielding of cosmic radiation cannot be found in the literature yet, which is most probably related to the relatively large amount of shielding material needed for reasonable effects, and the relatively low production rate of the electrospinning technique.

Another unexpected outcome of our literature survey is the lack of 3D-printed solutions, although some 3D-printing techniques can be used with embedded nanofibers or filaments, and 3D printing has long been an important technique in producing microsatellites and other spacecraft [112].

Apparently, while there is already much research going on to optimize shielding for spacecraft, there are still many blank areas on the map for researchers working on fiber finishing, but also on electrospinning, 3D printing with fibrous materials, and other techniques.

10. Conclusions

This review paper gives an overview of recent fiber-based shielding solutions for cosmic radiation. Generally, cosmic radiation—which can be subdivided into primary cosmic rays, mostly consisting of protons, alpha particles, and heavier bare nuclei, and secondary cosmic rays, also including pions, muons, neutrinos and photons—can have diverse undesired effects on the human body, such as carcinogenesis, DNA damage, and damages of the central nerve system. While high-energy particles can be shielded by materials containing hydrogen, high-energy photons are usually shielded by high-electron-density materials, such as lead.

This is why materials used for shielding of cosmic radiation are either based on light elements, such as hydrogen, like UHMWPE, boron-based materials, and carbon fibers, or contain heavy elements for X-ray shielding. Most research groups working on fibrous shields, however, concentrate on the first, since polyethylene and similar polymers are readily available in fibrous shape and can thus serve as a good base for further optimization.

In spite of the broad range of materials under investigation, there are still many unexplored areas in fiber-based materials, which suggests the possibility of transferring ideas from nanofillers to nanofibers, and generally from foils and sheets to fibrous composites, in this way enabling one to tailor the mechanical properties alongside the shielding efficiency of new material combinations. Such new shielding composites are necessary for diverse applications, from microsatellites to the next manned space mission.

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