Chapter 1

Introduction

High-energy heavy-ion accelerators facilitate the progress of accelerator science and research. Research topics, such as the discovery of new super-heavy and unstable nuclei, a new composition and damage research for material science, observation of the beam-plasma interaction and development of the inertial confinement fusion, clinical studies and treatments of the cancer therapy and radiotherapy surgeries, and the quest for the origin of the elements and the universe have benefited from the use of heavy-ion accelerators. Many heavy-ion accelerator facilities are now operating or are planned for construction in the world, and radioactive beam facilities using the spallation products from intense heavy ion beams are also under construction for various purposes. In these high-energy heavy-particle facilities, many secondary particles are created from nucleus-nucleus interactions, and these particles, especially neutrons, can produce radioactivities induced in accelerator and structural materials, air, water, and soil, and can penetrate through the facility building into the surrounding environment. It is therefore quite necessary to evaluate the emission of the secondary particles and the creation of the residual nuclei in various materials.

The high-energy heavy-ion constituents of cosmic radiation must also be considered in determining the risk to astronauts from radiation exposure in long-term missions, such as the extended stays on the International Space Station project (ISS) and prolonged missions to the moon and Mars. The interactions and transport phenomena of heavy ions in a medium including the human body must be well understood to estimate the dose absorbed by the patients during cancer treatment, to estimate the exposure of astronauts and scientists in space and to design the shielding of accelerator facilities.

1.1 Radiation in Space Environment

The ionizing radiation environment in space is very complex, consisting of a low-level background of galactic cosmic radiation (GCR), transient solar particle events (SPE), and, while in the Earth orbit, the trapped electron and proton radiation belts. Figures 1.1 and 1.2 show the elemental composition and the differential energy spectra of galactic cosmic radiation on the international space station (ISS) orbit calculated [1.1] by the GCR code CRÈME [1.2], respectively. The GCR energy range extends up to several hundred GeV and distributions have a peak at energies of several hundred MeV to 1 GeV. About 98% of the GCR consists of protons and heavy ions, and 2% consists of electrons. The former component contains 87 % protons, 12 % He, and 1 % heavy ions. The energy spectrum, flux, and composition of SPE changes by an orders of magnitude during solar flares, with energies from several MeV to several tens of GeV, as shown in Fig. 1.3. SPE contains about 80 - 90 % protons, 10 - 20 % He and about 1 % heavy ions.

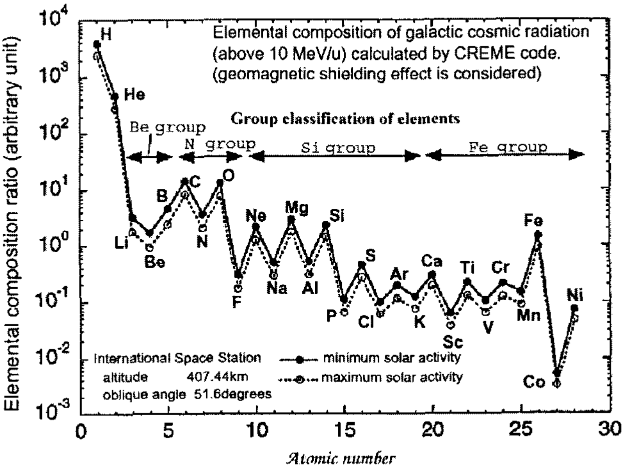

Figure 1.1: Elemental composition of galactic cosmic radiation on ISS orbits (courtesy of Ref. 1.1).

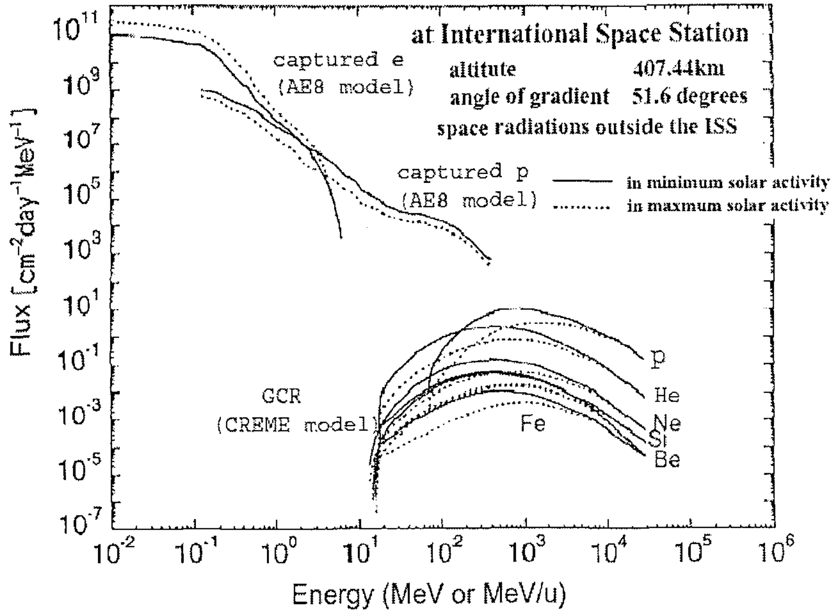

Figure 1.2: SPE and GCR energy spectra in the ISS orbit [1.1] calculated by the CRÈME code (courtesy of Ref. 1.2).

When these radiations traverse the shielding material of a space vehicle, they interact with the constituent elements through specific atomic and nuclear processes, including breaking up of ions into smaller fragments and producing secondary radiation that can penetrate more deeply into or through the material. The composition and intensity of these transmitted radiations (secondaries and fragments) depend on the elemental constituents of the specific materials. The radiation-induced injury in biological tissue depends on the composition and intensity of the transmitted particles. An extremely important secondary particle component in this respect is the neutron, which has no charge and its flux can not be reduced in atomic interactions thus being extremely damaging to biological tissue. Current theoretical models have shown the secondary neutrons to be a major contributor to exposures within possible lunar habitats and on the Martian surface, and recent studies have shown that neutrons could comprise 30 to 60 percent of the dose equivalent on the ISS (International Space Station). A recent review of the neutron flux in the Earth's atmosphere has raised serious questions about the adequacy of our understanding of the production and propagation of neutrons by GCR in atmospheric components. Any advances in the specification of shielding for habitats on the moon or Mars require measurements of the transmitted neutron component within lunar and Martian shielding materials and improvements in databases and computational procedures.

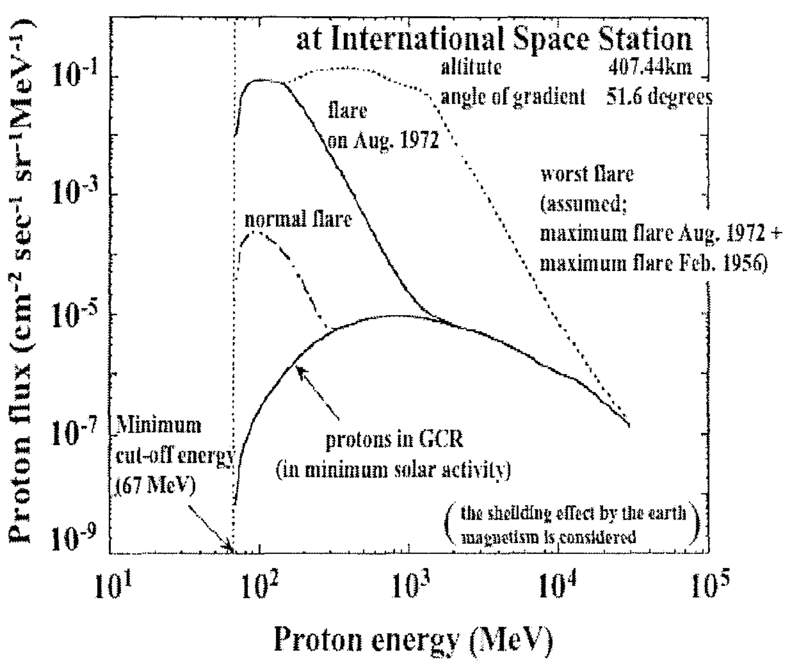

Figure 1.3: SPE and GCR proton energy spectra in the ISS orbit [1.1] calculated by the CRÈME code (courtesy of Ref. 1.2).

1.2 Heavy-Ion Accelerators for Medical Applications

It is important to use a type of radiation, which is well suited to medical treatment, especially in cancer therapy. The curative effect can be compared using the relative biological effectiveness (RBE) and the oxygen enhancement ratio (OER). Fast neutrons and heavy ions exhibit three times the RBE and half times the OER of gamma rays and electrons, which are conventionally used in cancer therapy, as shown in Fig. 1.4.

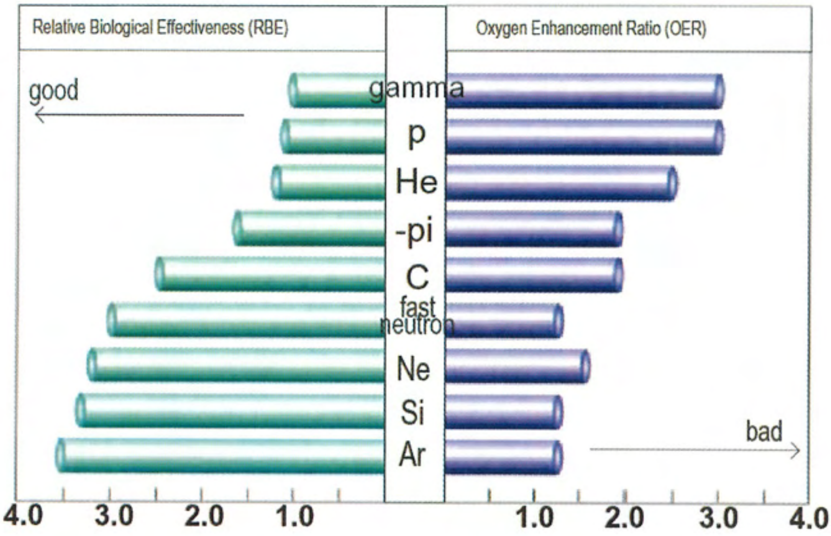

Figure 1.4: Relative biological effectiveness RBE and oxygen enhancement ratio OER of various radiations from gamma ray to Ar particle (courtesy of Ref. 1.3).

It is also important to avoid exposing normal tissue to the radiation. For this purpose, a good evaluation of the profile of the depth-dose distribution in the human body is required. Figure 1.5 shows the dose distributions in the human body of various radiations. Gamma rays and neutrons give the largest fraction of dose in the vicinity of the surface of the body (on the skin). They attenuate with depth, but reach deeply inside the body, where the normal tissue is located. It is possible to give a higher dose to a tumor in a deep position of the body by using the cross-firing method, however this method needs much time and complex processes for clinical treatment planning. Compared to gamma rays and neutrons, protons and heavy ions give a high dose locally just before stopping, as shown in Fig. 1.5. By using this strong localization of the depth-dose distribution, the tumor area can be locally irradiated while keeping the normal tissue under a low dose field.

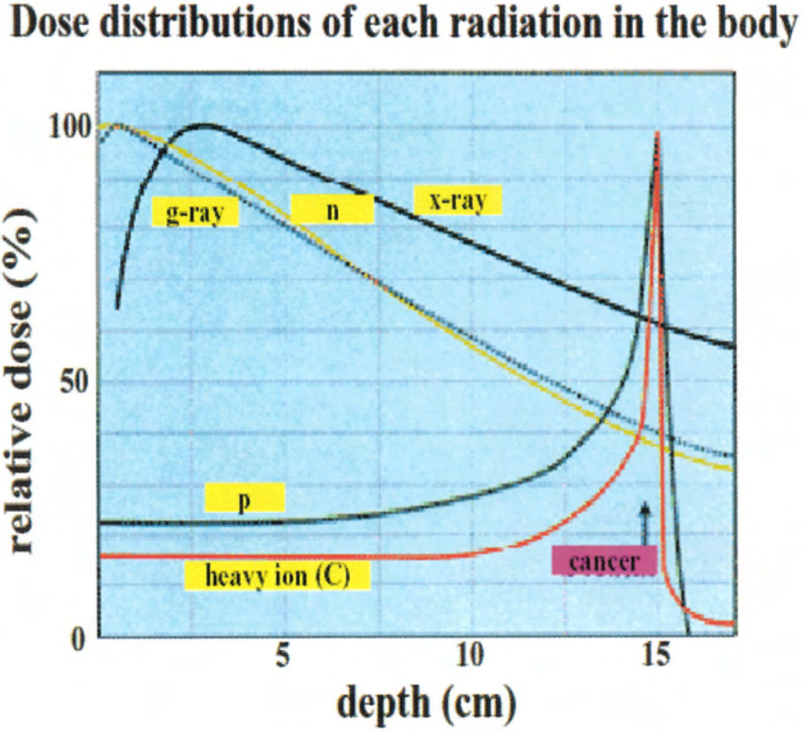

Figure 1.5: Dose distributions in the human body of various radiations (courtesy of Ref. 1.3).

From 1977 to 1992, 223 patients were treated with charged particles at the Lawrence Berkeley Laboratory (LBL), USA, for treatment of skull tumors, with good success. The Harvard Cyclotron Laboratory (HCL), in association with Massachusetts General Hospital (MGH), USA, has been treating patients with proton beam continuously since 1961. In 1985 a consortium of physicians, physicists and engineers formed an international working group, the Proton Therapy Cooperative Group (PTCOG), to further advance the study of clinical proton beam therapy. In 1990, Loma Linda University Medical Center (LLUMC), USA became the first proton beam treatment center dedicated to clinical cancer treatments.

Heavy-ion therapy began at the Bevalac, Lawrence Berkeley Laboratory (LBL), in 1975, first using a Ne ion. That therapy program continued until the Bevalac was decommissioned in 1992. Since 1994 the HIMAC (Heavy Ion Medical Accelerator in Chiba) at the National Institute of Radiological Sciences (NIRS), Japan, has being operated for heavy-ion therapy, mainly using C beams. More recently, heavy-ion therapy started running at SIS (SchwerIonen Synchrotron) at GSI (Gesellschaft fuer Schwerionenforschung), Germany, using C ions from 1998, and at the Hyogo Ion Beam Medical Center, Japan using C ions from 2002. In addition there are many other facilities in the world, which employ proton and heavy-ion therapies.

The data on secondary particles ejected from the target and the spallation products in the target bombarding by the heavy ion beam are quite important to estimate the source terms of the accelerator shielding design and also to calculate the dose delivered in the human body during the therapeutic irradiation.

1.3 Radioisotope (RI) Beam Factory in Large-Scale Heavy-Ion Accelerators

In recent years the advent of radioisotope (RI) beams has opened up a number of new fascinating scientific fields. The RIKEN (Institute of Physical and Chemical Research) Accelerator Research Facility (RARF), Japan has undertaken construction of the RI beam factory (RIBF) as a next generation facility that is capable of providing the world's most intense RI beams over the whole range of atomic masses. The other RI beam facilities worldwide are:

ATLAS: Exotic Beam Facility at ANL, U.S.A

ISOLDE: Isotope Separation On Line Facility For Production of Radioactive Ion Beam at CERN

GANIL: Grand Accelerator D'Ions Lourdes, France

International Accelerator Facility at GSI, Germany

HRIBF: Holifield Radioactive Ion Beam Facility at ORNL, U.S.A.

ISAC: Isotope Separator and Accelerator at TRIUMF, Canada

E-Arena: Exotic Beam Facility at KEK, Japan.

These accelerators can accelerate very intense high-energy heavy-ion beams in order to produce sufficient yields of radioisotope beams through projectile and target fragmentation. Because of the high intensities used at these accelerators, it is very important in the design phase of the facility to evaluate the potential for radiation damage to the local materials (accelerator and structural materials, air, water, and soil), as well as evaluate the potential radiation exposures to humans (radiation workers and nearby inhabitants) in and around the facility. The high-energy heavy ion potentially creates a large amount of secondary fragments and residual nuclei when interacting with other nuclei. In the case of secondary particles, heavy ions are stopped readily in materials; however, they produce secondary particles through subsequent nuclear reactions before stopping. Secondary neutrons and gamma rays of no charge, especially neutrons, strongly penetrate the shielding and must be carefully considered in the design.

1.4 Purpose of This Handbook

When one of the authors, Nakamura, did the shielding design of the HIMAC heavy-ion medical accelerator facility more than 15 years before, there existed no available experimental data on neutron production from heavy ions and no available computer codes for the heavy-ion transport calculation at all. Therefore, we had to use the neutron production from He ions as a source term in the shielding design [1.4], which was calculated by the HERMES code [1.5]. Later, we confirmed that the calculated results gave a large overestimation to the only existing experimental result by Cecil *et al.* [1.6] at the time.

Now, the HIMAC accelerator has been operating continuously for almost ten years, and our group has done systematic experiments to measure neutron TTY (Thick Target Yield) using the HIMAC heavy-ion beams. The measured results were actually used for the shielding design of the RIKEN RIBF. In addition, various other experiments have been done on secondary particle production and transport by heavy-ions for the past ten years at HIMAC. In this handbook, we compiled these experimental results along with some experimental results taken using other heavy-ion accelerators. In this handbook, we also included the calculation models and codes for heavy ion reaction and transport. The numerical data recorded in the CD Rom is attached in the handbook. We do hope that this handbook will be useful for various applications.