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Development and evaluation of the Combined Ion and Neutron Spectrometer (CINS)

C. Zeitlin [a,*], R. Maurer [b], D. Roth [b], J. Goldsten [b], M. Grey [b]

[a] *Lawrence Berkeley National Laboratory, Life Sciences Division, 1 Cyclotron Road, MS 74R0197, Berkeley, CA 94720, USA*
[b] *Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA*

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ABSTRACT

The Combined Ion and Neutron Spectrometer, CINS, is designed to measure the charged and neutral particles that contribute to the radiation dose and dose equivalent received by humans in spaceflight. As the depth of shielding increases, either onboard a spacecraft or in a surface habitat, the relative contribution of neutrons increases significantly, so that obtaining accurate neutron spectra becomes a critical part of any dosimetric measurements. The spectrometer system consists of high- and medium-energy neutron detectors along with a charged-particle detector telescope based on a standard silicon stack concept. The present version of the design is intended for ground-based use at particle accelerators; future iterations of the design can easily be streamlined to reduce volume, mass, and power consumption to create an instrument package suitable for spaceflight. The detector components have been tested separately using high-energy heavy ion beams at the NASA Space Radiation Laboratory at the Brookhaven National Laboratory and neutron beams at the Radiological Research Accelerator Facility operated by Columbia University. Here, we review the progress made in fabricating the hardware, report the results of several test runs, and discuss the remaining steps necessary to combine the separate components into an integrated system. A custom data acquisition system built for CINS is described in an accompanying article.

1. Introduction

The space radiation environment presents potential health hazards to crew and equipment [1–4] owing to the presence of energetic charged particles and, in shielded environments, neutrons. In particular, the Galactic Cosmic Rays (GCR) are a source of a more or less constant flux of energetic nuclei, on the order of 0.2–0.5 particles per cm^2 per second per steradian [5]. Many GCR have high energy (near solar maximum, about half the particles have kinetic energies above 1 GeV/nucleon) and are therefore able to penetrate significant depths of shielding. In terms of abundance, protons dominate the flux (85–90%), helium ions make up most of the rest, and highly-charged ions such as silicon (charge $Z = 14$) and iron ($Z = 26$) are rare, representing about 1% of the total. However, because the dose delivered by an energetic particle is proportional to the square of the charge, the heavy ions make a substantial contribution to dose. To relate the physical properties of a mixed-field radiation environment to biological risk, dose equivalent is calculated by integrating the quality factor Q [6] against the linear energy transfer (LET or L) spectrum.[1] When dose equivalent contributions are calculated for the GCR in unshielded space, the importance of heavy ions grows even larger, and iron accounts for the single largest contribution of any ion species. This is because the LET of high-energy iron ions in water is about 150 keV/μm, close to the peak of Q(L) at 100 keV/μm.

The other main source of energetic particles in deep space is the sun, when it produces solar particle events (SPEs). SPEs are sporadic, being more likely near solar maximum, and predominantly produce protons at relatively low energies. Typically the flux falls rapidly with energy and is negligible above 100 MeV; such a spectrum is said to be "soft." In some instances SPEs can be extremely intense and/or have a "hard" spectrum with significant fluxes above 100 MeV [7]. Some events [8] contain significant fluxes of high-energy heavy ions.

Efficient mechanisms exist that allow DNA to correctly repair itself when there is simple damage along a strand [9]; this sort of damage can be caused by, among other things, the low-LET radiation from cosmic ray muons on the surface of the Earth. However, high-LET radiation can produce more complex damage sites [10]. These sites may be unrepairable, leading to cell death, or, worse, they may be mis-repaired, possibly leading to mutagenic changes. Data on the biological effects of high-LET radiation have historically been sparse, and effectiveness as a function of LET is strongly dependent on the system and endpoint studied. Thus high-LET radiation presents a source of risk that is difficult to quantify with confidence. Uncertainties in biological response are and will

* Corresponding author. Tel.: +1 510 486 5518; fax: +1 510 486 6949.
E-mail address: cjzeitlin@lbl.gov (C. Zeitlin).

[1] We refer to LET in water, in an infinite volume so that all ionization electrons are included, even high-energy delta-rays that escape small volumes such as cells. This is sometimes written LET_{∞}.

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continue to be the limiting factor in risk assessment for long-duration mission planning purposes for the foreseeable future [11].

Although energetic, highly-charged ions have high LET, their fluxes and their contribution to risk can be reduced by shielding, particularly if hydrogenous materials are used, for reasons explained elsewhere [12–14]. The mechanism for the reduction of dose and risk is nuclear fragmentation, in which the projectile nucleus is broken up into lighter, less ionizing particles. Neutrons are also produced in these interactions and become increasingly important as shielding depth increases [15]. Though neutrons are not directly ionizing, they deposit energy (and therefore deliver a dose) through their interactions with nuclei. In tissue, interactions with hydrogen are particularly important because the full energy of the neutron can be transferred, giving a proton considerable range.

Because they do not lose energy through the ionization process, neutrons are more difficult to attenuate than charged particles. There are two principal ways in which neutrons are created in nuclear interactions. In nucleus–nucleus collisions, neutrons can be removed from the projectile, emerging from the interaction with velocities similar to that of the projectile, modified by the Fermi motion of the nucleons. These neutrons are sometimes referred to as "projectile-like." The second mechanism is evaporation from target nuclei that receive significant excitation energy in the collision with the projectile. These excited states decay by (isotropic) emission of nucleons. Although these target-fragment neutrons have low energy, they can escape the target or shield and contribute to the dose in tissue.

Measurement of the mixed radiation field in space requires a highly capable instrument or instrument suite that must be designed and implemented within severe mass and power constraints and many technological advances have been made as a result of these constraints. An instrument suite with similar capabilities but intended for ground-based applications is free of the mass and power constraints, but nonetheless many advantages can be gained from incorporating flight-tested or flight-like components into ground-based systems. CINS benefits from technology developed for spaceflight, particularly in the area of data acquisition, with the result being a compact, portable system, optimized for making measurements at heavy ion accelerators.

2. Detectors and electronics

Given the complexity of the space radiation environment, particularly behind moderate depths of shielding, detailed measurements will require multiple types of detectors, each optimized to measure a specific component of the environment. CINS therefore contains three sub-systems: a large plastic scintillator which measures neutrons in the energy range from 1 to 15 MeV, where their biological effectiveness is high; a silicon detector system with a veto counter for the measurement of high energy neutrons; and a silicon detector stack augmented with three scintillators, two of them thin plastic and one fairly thick BGO crystal, for detection and identification of charged particles from protons to iron. As the sub-systems are not yet integrated, we have performed separate tests on each, which are described below.

There is considerable commonality in the readout requirements of the different systems, particularly between the two systems based on silicon detectors. These detectors require a charge-sensitive preamplifier, located close to the detector itself to minimize cable lengths and the attendant noise pickup, and generally a shaping amplifier is used to improve performance. The job of the shaper is to filter and amplify the output of the preamplifier to improve the signal to noise ratio, and – because fall times from the preamplifiers can be long – to restore the signal to baseline soon after the peak.

2.1. Neutron detectors

2.1.1. Eljen fast neutron detector system

For the Neutron Energy Spectrometer, JHU/APL has designed, procured and fabricated a 12 cm × 12 cm Eljen plastic boron-loaded scintillator for detection of medium-energy 1–15 MeV neutrons that have the maximum dose equivalent weighting factors of 10–20 [6]. The large scintillator is mated to a photo-multiplier tube and the detector system uniquely identifies "fast" neutrons by observing a combination of a recoil or scatter pulse and a subsequent ^{10}B capture pulse that occur within a narrow time window. The average time separation of the pulses is about 2 μs. This detector system was calibrated at Columbia University's Radiological Research Accelerator Facility (RARAF) in November 2006 and was used at NSRL for the first time in May 2007.

The medium-energy neutron detector system uses a unique trigger technique to positively identify neutrons. The two pulses described above, with their particular time and amplitude restrictions, distinguish the waveform produced by a neutron in the energy range of interest from waveforms produced by other particle types. The first pulse represents the energy of the incoming neutron which interacts and slows down within the detector; the second pulse represents the boron capture of the slowed neutron. The timing of the second pulse with respect to the first pulse is critical. The allowable time window is based on a few criteria, the first of which is the e-folding time of a capture given the size of the detector and the amount of ^{10}B present. Dead time and observations during calibration help determine what time restriction to use. The second pulse also has restrictions on both its minimum and maximum height. This trigger technique is less efficient at detecting neutrons than use of other anti-coincidence techniques, but given the size and volume of the detector it is a reasonable approach. The trigger has been implemented in NIM electronics for our accelerator experiments. It is based on heritage from the Gamma-Ray Neutron Spectrometer (GRNS) flying on the MESSENGER spacecraft [16], in which the full trigger logic is implemented in the FPGA firmware.

2.1.2. High-energy neutron system (HENS)

A 5 mm thick lithium-drifted silicon detector is sensitive to neutrons with energies greater than 10 MeV via elastic and inelastic neutron–silicon interactions that produce charged particles within the active volume of the detector. Charged silicon recoils (elastic reaction) and secondary particles such as protons, alpha particles and residual nuclei (inelastic reactions) deposit charge in the detector. This charge is subsequently collected and measured by standard pulse height techniques. Thicker detectors offer increased efficiency for neutron detection by containing a greater number of possible interaction sites for the neutron, and consequently presenting a greater fraction of the mean free path to incident neutrons. This fact is especially important as the neutron energy increases to tens of MeV. The efficiency of the 5 mm thick detector was determined by exposure to mono-energetic neutron beams in experiments at the Columbia University RARAF. The measured efficiency is about 5% in the interval from 5.89 to 18.5 MeV. The agreement between our data and models indicates that we can achieve efficient detection (3% or greater) of neutrons with energy up to about 50 MeV [17]. Since the cross section for $(n + A)$ reactions falls with energy in this region, the efficiency of the method also falls, to about 1–2% at 100 MeV [18].

To separate the neutrons from the other incident radiation such as charged particles and gamma rays requires an anti-coincidence