Compact Ion and Neutron Spectrometer (CINS) for Space Applications

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Abstract–**We are developing a Combined Ion and Neutron Spectrometer (CINS) for space applications inside interplanetary transport vehicles and on planetary surfaces. Our concept for a charged particle telescope includes thick silicon detectors and both thin and thick scintillators. The neutron spectrometer has been under development since 1997 with versions being flown on aircraft and balloon flights. We present 1) charge and energy spectra for the thick silicon detectors from heavy ion experiments; 2) typical neutron prompt and delayed pulse height spectra from neutron accelerator beam experiments; and 3) simulations from modeling of the compact charged particle telescope showing ion species identification and energy deposition spectra.**

I. INTRODUCTION

THIS paper reports on an instrument development funded by NSBRI (The National Space Biomedical Research Institute) for concept and design of a Combined Ion and Neutron Spectrometer for use as a compact radiation monitor on future interplanetary transport and landing vehicles. The intent of this instrument is to monitor the parts of the radiation environment in habitats that are relevant to the radiation health risk astronauts will experience on long interplanetary missions such as a base on the Moon and a round trip to MARS. The specific objectives are to 1) design and fabricate a prototype Combined Ion and Neutron Spectrometer (CINS) for space applications; 2) calibrate and evaluate the response functions of the CINS detector systems using ground-based accelerator beams of appropriate type and energy; 3) use CINS in a ground based accelerator comparison with traditional space instrumentation such as the Tissue Equivalent Proportional Counter (TEPC); and 4) evaluate the effects of radiation shielding materials as countermeasures by measuring charged and neutral secondary particle generation from a simulated space environment.

High-energy charged particles of galactic and solar origin pass through or undergo nuclear interactions with spacecraft structures in space. These primaries create a number of secondary particles inside the relatively thick structures that, combined with the surviving primaries, can produce a significant ionizing radiation environment. This radiation is a threat to long term inhabitants or travelers for space missions and produces an increased risk of cancer, cataracts and Central Nervous System (CNS) damage. High-energy collisions with common spacecraft materials such as aluminum and silicon create secondary particles inside structures that consist of protons, neutrons, heavy ion fragments and pions. The energy range of the protons and the high-energy heavy ions require a detection system with several orders of magnitude of dynamic range. Neutrons are electrically neutral and difficult to measure and detect, especially at the high-energy end of the spectrum. Together the heavy ions and neutrons produce the largest energy depositions in the shortest distance or path length of tissue deep in the astronauts' bodies so that fewer collisions or shorter ionization paths can deposit relatively large radiation doses in localized volumes compared with the more numerous protons.

CINS improves upon existing charged particle species and energy spectrometers (e.g., MARIE [1] on the Mars Odyssey mission and the similar charged particle spectrometers aboard the International Space Station) and incorporates the capability of the previously developed NSBRI Neutron Energy Spectrometer to yield a single and complete ionizing radiation environment monitor. An improved charged particle/ion telescope detector system is being designed at University of California Lawrence Berkeley National Laboratory (LBNL) with modeling of the telescope concept and its response at the Johns Hopkins University Applied Physics Laboratory (JHU/APL). It will be combined with the NSBRI Neutron Energy Spectrometer at JHU/APL into a single instrument for ground based research at accelerators by using multiple fast channels of analog and digital electronics based on JHU/APL's experience with NEAR and MESSENGER spacecraft instruments.

After fabrication and calibration, CINS energy spectra will be compared with the Tissue Equivalent Proportional Counters (TEPC) and dosimeters in ground-based accelerator experiments to investigate basic hypotheses about the lack of radiation environment information from these conventionally used monitors due to detection limitations with respect to high energy protons, low energy heavy ions and almost all neutrons. CINS also adds the capability to measure the increased risk due to the multiplication of primary beams of protons and heavy ions by spacecraft materials in beam-thick target interactions [2] which produce a secondary particle environment of protons, neutrons and heavy ion fragments

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Manuscript received November 2, 2005. This work was supported by the National Aeronautics and Space Administration under NASA Cooperative Agreement 9-58 with the National Space Biomedical Research Institute.

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inside transport vehicles or on planetary surfaces. Comparison of conventional and new spacecraft structural/shielding materials will be accomplished by evaluating the “internal” radiation environment.

II. CHARGED PARTICLE DETECTION

The detection of all biologically relevant energetic charged particles in spaceflight presents many challenges. Abundant galactic cosmic rays (GCRs) include ions from hydrogen to iron at energies from 20 MeV/amu to 10 GeV/amu. The GCRs span a large range of energy loss, about four orders of magnitude. Identification of particle type and energy therefore requires a detector with extremely low noise, wide dynamic range, and a large enough geometry factor to obtain sufficient statistics on the rarer heavy ions such as silicon and iron. In addition to GCRs, that arrive at a low rate (< 1 cm^{-2} sr^{-1} s^{-1}), intermittent Solar Particle Events (SPEs) can produce large fluxes of lower energy protons with spectra falling sharply above 100 MeV. Though these protons are stopped by modest depths of shielding, they can produce high fluxes of secondary neutrons inside a spacecraft and can deliver large doses to astronauts performing an EVA where the only shielding is provided by the spacesuit. A flight detector must be capable of measuring solar protons below a few hundred MeV at very high rates.

We need re-drifted Si(Li) detectors for both charged particles and neutrons so eight of dimensions of 4cm in diameter by 5mm in thickness are being refurbished from LBNL’s existing stock. These were fabricated in the late 1980’s and have been used a few times per year in accelerator experiments. The first step in refurbishing them is to restore optimal distribution of lithium throughout the silicon lattice by a re-drifting process, which consists of thermal cycling under bias voltage. The next step is the creation of a guard ring, accomplished by routing out the detector in a circular pattern at a fixed radius. A second electrical contact is added for the area outside the ring. The area inside the ring becomes clearly defined, allowing for accurate calculation of the detector’s geometry factor, and its performance is also substantially improved. By reading out both the inner and outer surfaces, one can also obtain some information about tracking and particle multiplicity. Fig.1 shows a photograph of a refurbished detector.

As of June 2005, eight detectors have been refurbished, four with guard rings added and four without. The four detectors without guard rings were tested in heavy ion beams at the Heavy Ion Medical Accelerator in Chiba, Japan (HIMAC) in February 2005. Detector performance in all cases was greatly improved compared to performance prior to refurbishing, with quiescent noise levels of approximately 100 keV. These detectors will be returned to the LBNL Solid State Detector Laboratory (SSDL) for the addition of guard rings in Fall 2005. The four detectors that have already had guard rings added are scheduled for evaluation during 2005 at the Brookhaven National Laboratory (BNL) AGS accelerator. On the test bench, these units displayed noise levels of about 30 keV. Their active diameters, which have been reduced by the guard rings, were measured with a collimated α particle source and found to be 37 mm.

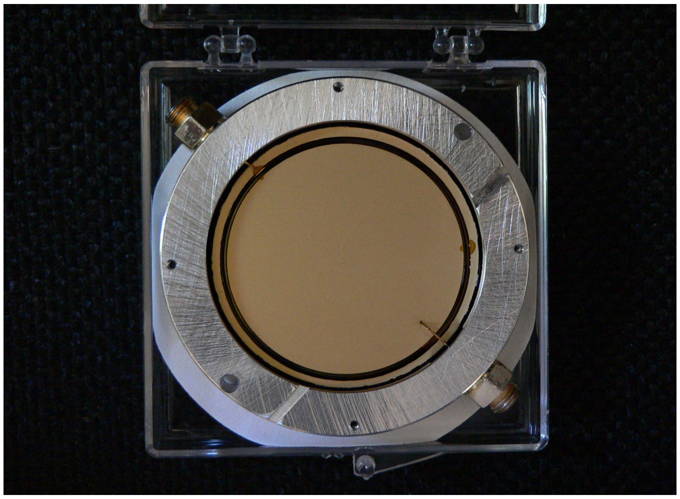

Fig. 1. Photograph of a refurbished 4cm diameter X 5mm thick lithium drifted silicon detector with a guard ring that defines the active diameter as 3.7cm.

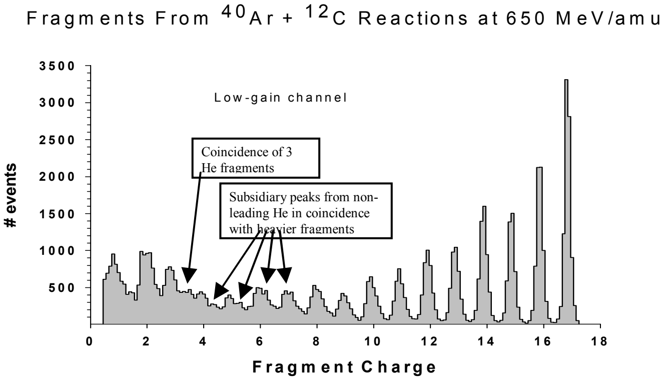

Fig. 2. Charged fragment spectra from the collision of a 650 MeV/amu beam with a carbon target at the HIMAC accelerator detected with a re-drifted 5mm thick Si(Li) detector. A dynamic range of 400:1 and resolution sufficient to resolve peaks from detection of multiple fragments in coincidence was demonstrated. (E.g., an effective $Z = (6^2+2^2)^{1/2} = 6.3$ from coincidence of C and He.)

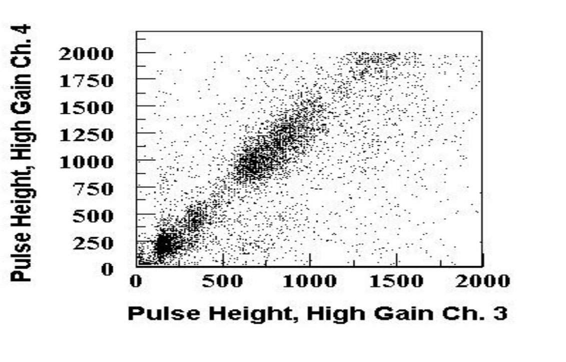

Fig. 3. Scatter plot from two pulse height channels of an argon-polyethylene collision.

Results from the re-drifted detectors tested in at the HIMAC are shown in Figs. 2 and 3. Fragmentation of 650 MeV/amu ^{40}Ar ions was measured in several targets. Typical charge spectra obtained with a carbon target are shown in Figure 2.

A scatter plot of high-gain channels obtained with a 1.98 g cm^{-2} CH_2 target is shown in Figure 3. The cluster of events in the bottom left-hand corner of the plot are protons; the nearby, fainter cluster indicates events in which two protons were detected; and the large, diffuse cluster near the center of the plot is due to events with a helium fragment and (in some events) one or more protons detected in coincidence. The dynamic range and charge resolution evidence shown in Figs. 2 and 3 demonstrate the suitability of the re-drifted Si(Li) detectors for CINS.

III. NEUTRON DETECTION

In 1997 JHU/APL proposed to design and build a portable, low power and robust neutron spectrometer that measures the neutron spectrum from 10 KeV to 500 MeV with at least 10% energy resolution in the various energy intervals. This instrument can monitor the existing neutron environment both inside spacecraft structures and on planetary surfaces to determine the safest living areas, warn of high fluxes associated with solar storms and assist in making an accurate assessment of increased cancer risk, DNA and central nervous system (CNS) damage to astronauts. The instrument uses a highly efficient proportional counter Helium 3 tube at the lowest energy intervals where equivalent damage factors for tissue are the highest (10 KeV-2 MeV). The Helium 3 tube can be shielded with a cadmium absorber to eliminate the much less damaging and, hence, uninteresting, but more prevalent, thermal and epithermal neutrons and to make the structure of the spectrum more accurate in the 20 KeV-2 MeV range.

Subsequent investigations and experiments convinced us to add a Bicron 454 scintillation detection system monitored by a photomultiplier tube for the fast neutrons between 1-20 MeV. For the highest energy neutrons the spectrometer uses a 5mm lithium drifted bulk silicon solid state detector in the neutron energy range of 20-600 MeV due to its demonstrated and modeled detection efficiency of 3-5% in this energy range. In high-energy regions equivalent damage factors for dose equivalent are lower but hits from one or a small number of neutrons may prove to be important in sensitive localized volumes. The silicon detector system for high-energy neutrons discriminates against charged particles by using a cesium iodide scintillator of an appropriate geometry surrounding the silicon detector volume monitored by a photo-multiplier tube.

The high-energy neutron response function with 5mm thick Si(Li) detectors in a neutron energy range from 20 to 600 MeV was developed experimentally at the Los Alamos Neutron Science Center (LANSCE). The key verification of the response function is shown in the results of a blind experiment in Fig.4. The blind experiment was performed with LANSCE personnel arranging a beam-target collision in the switch yard in a configuration unknown to us. After we deduced our detector response function and the incident neutron spectrum, it was compared with the previously unknown LANSCE calculation of the same spectrum. Our success in deducing the incident neutron energy spectra from energy deposition spectra in these silicon solid state detectors has been reported in 2003 [3].

Medium-energy neutron data (1-20 MeV) with a Bicron 454 scintillator from recent calibration runs in April 2005 at the Columbia University Radiological Research Accelerator Facility (RARAF) are shown in Fig. 5. Neutrons are positively distinguished from gamma rays and charged particles by the double-peaked spectra that indicate the capture of a scattered and slowed neutron by the boron loading in the scintillator with a delay of a mean of 2 microseconds. The height of the first peak is calibrated to yield the energy of the subsequently captured neutron.

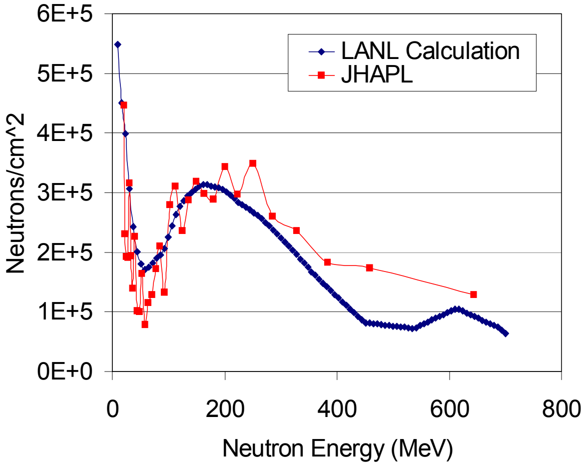

Fig.4. Comparison of the deduced incident neutron energy spectrum from the JHU/APL experimental 5mm Si(Li) detector response function (connected squares) with the LANSCE determination of the same spectrum (continuous crosses) for the switch yard beam-target collision configuration in a blind experiment.

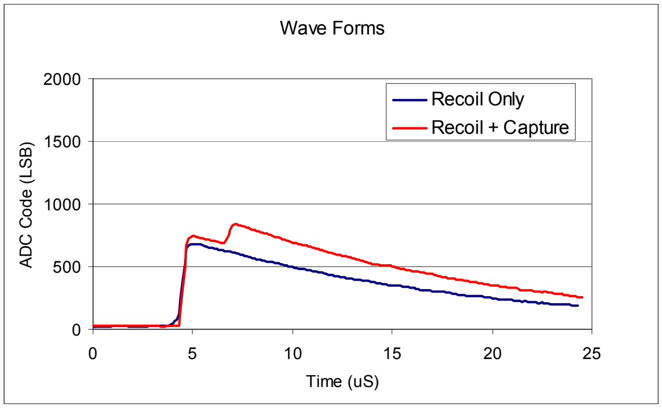

Fig. 5. Typical waveforms from the scatter and capture of 6 MeV neutrons by the boron-loaded Bicron 454 scintillator detector are shown. The single peak plot shows just a scatter. The double-peaked plot indicates a scatter and a capture that can only be a neutron.

IV. CHARGED PARTICLE TELESCOPE MODELING

We have completed a preliminary model of the charged particle telescope using the GEANT4 high-energy transport code. This model allows us to rapidly modify our conceptual design based on the desired dynamic range and to ensure that we can cleanly distinguish between electrons, protons and heavy ions. We have also examined and verified the effects of the asymmetry of the design.

Our GEANT4 detector geometry consists of a front 1 mm thick circular slab of BC454 followed by a 5mm thick circular Si solid state detector, then a second 1 mm BC454 detector, followed by three 5mm Si detectors and finally a 30mm thick BGO detector. The entire detector stack, shown in Fig.6, is surrounded by a titanium cylinder that is 2mm thick. The entire telescope stack is only 6.4 cm in length. It is similar to MARIE in that 4 thick Si detectors provide particle identification and LET spectra. The BGO adds mass, stops protons up to energy of 150 MeV and makes the stack asymmetric for directionality purposes. The plastic scintillators are used as triggers and simple counters which is helpful in high-rate environments.

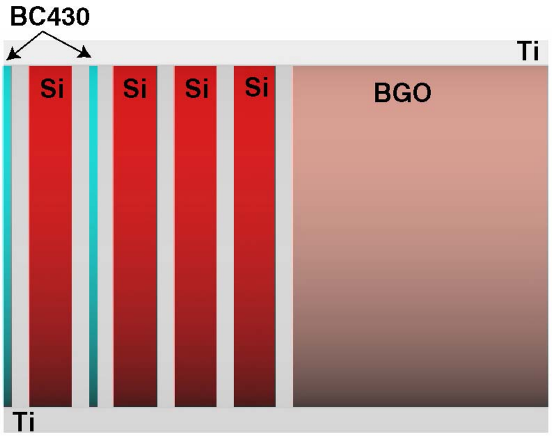

Fig. 6. Conceptual design of the seven detector element charged particle telescope from GEANT4 modeling. The BC430 scintillators are each 1 mm thick; the Si(Li) detectors are 5mm thick and the BGO scintillator is 3 cm thick. The telescope diameter is 4 cm; its length is 6.4 cm.

The modeling results in Fig. 7 indicate that differential channels for protons can be created up to ~500 MeV with one integral channel E> 500 MeV. The results also show that we can distinguish the electron, proton, helium, oxygen and iron groups in the cosmic rays in a manner sufficient for biomedical dose equivalent measurement.

Fig. 7A shows the energy deposition in the thick BGO detector on the abscissa with the energy deposition in the last Si(Li) Solid State Detector (SSD) on the ordinate. The vast majority of the protons can be separated from the electrons which was a primary concern for a space environment. With the BGO the GEANT4 simulation shows that protons up to ~300 MeV can be uniquely identified. Fig. 7B and Fig. 7C show that a proton depositing ~80 MeV in the BGO yields primary and penetrating depositions in SSD4 of 1 MeV resolution.

V. CINS INSTRUMENT

A block diagram of the CINS instrument is shown in Fig. 8. The heritage of the instrument derives from several sources. The low- and medium-energy neutron sensors were used on the Mars Odyssey and Mercury MESSENGER missions. The low- and high-energy neutron detectors were originally funded for development for the subsequently cancelled Mars 2003 Lander [4]. The high-energy sensor has been used on balloon flights and in thick target accelerator experiments.

Charged-particle detectors built by Lawrence Berkeley National Laboratory have flown on the Voyager, ACE/CRIS, MARIE, etc. space missions.

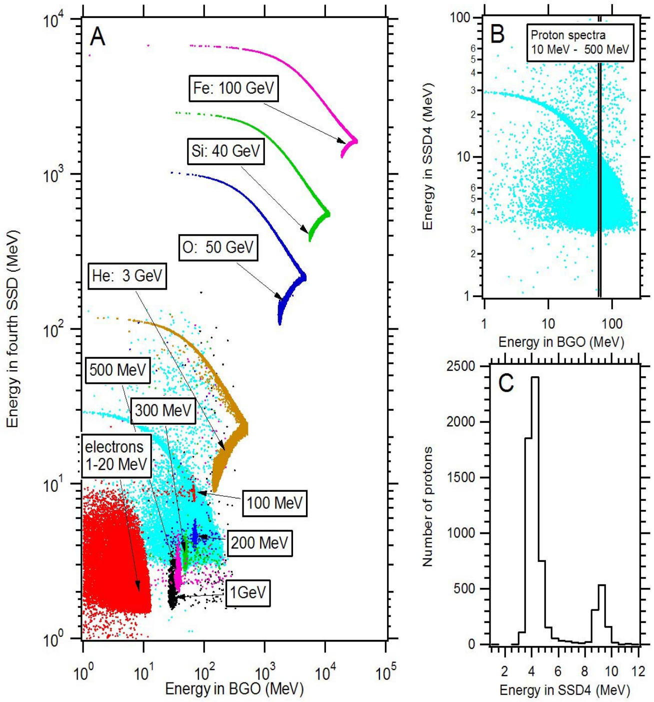

Fig. 7. Results of the GEANT4 modeling of the charged particle telescope shown in Fig. 6. Fig. 7A shows the separation in energy depositions for the fourth silicon solid state detector (SSD) and the BGO scintillator for electrons, protons and the helium, oxygen, silicon and iron heavy ion groups. Fig. 7B and Fig. 7C show that a proton depositing 80 MeV in the BGO has an energy resolution of 1 MeV in SSD 4.

JHU/APL built similar instrument electronics for the MESSENGER Gamma Ray/Neutron Spectrometer (GRNS).

The CINS instrument objectives were refined with respect to specific metrics in February/March 2005 so to

1) eliminate the gain saturation of MARIE for heavy ions with LET > 35 keV/micron;
2) increase the dynamic range vs. the MARIE instrument by a factor of about 100 up to 10000:1 to include protons with energies above 100 MeV;
3) increase the maximum instrument event detection rate by at least a factor of 30 to a minimum of 100 Hz.

We think that the above instrument goals are readily achievable given the flight and development experience of the investigators involved.

To date we have had eight 5mm thick Si(Li) re-drifted with guard rings being added to four of them. The remaining four detectors will be completed in FY 2006. These thick detectors will be used in both the charged particle telescope and for the high energy neutrons in our accelerator experiments.

The boron-loaded scintillator had been procured and delivered. It must be wrapped in a light tight manner and mated to a photomultiplier detector before it can be calibrated.

During FY 2006 we must procure the BGO scintillator, complete the mechanical design and start the instrument assembly. We will continue to refine the GEANT4 modeling of the charged particle telescope and the high-energy neutron detector.

Experiments at the NASA Space Radiation Laboratory are planned for individual detectors during the spring of 2006 with initial experiments with the charged particle telescope in late 2006.

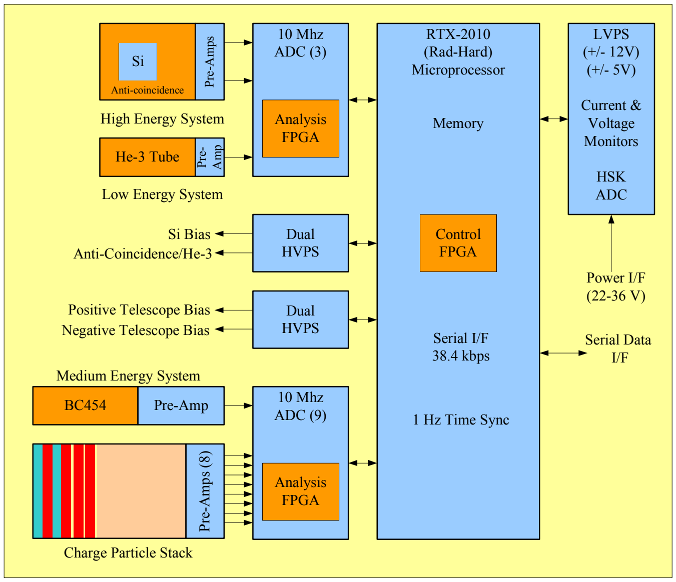

Fig. 8. Conceptual block diagram of the CINS instrument. The basic concept is derived from the JHU/APL MESSENGER GRNS instrument and [4].

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