On the Use of Superheated Bubble Detectors on Space Missions

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Outline

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- Proton Experiments at ProCure Proton Treatment Center, Oklahoma City, OK USA
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Introduction and Motivation

- Canadian made Bubble Detectors have been flown aboard the Russian Mir Orbital Station and the International Space Station (ISS), in joint studies between the Canadian Space Agency (CSA), the Russian Institute of Biomedical Problems (IBMP), Bubble Technology Industries and several Canadian universities.
- The aim of these studies has been to measure the neutron contribution to total ionizing radiation dose equivalent received during space flight and have resulted in numerous publications [1-6].
- The interpretation of the results has been questioned by some members of the space radiation dosimetry community. Namely there have been questions regarding the mechanism responsible for bubble formation and the sensitivity of bubble detectors to charged particles, including the energetic protons and heavy ions encountered during space flight[7-9].
- There have also been questions on how the dose equivalent measured by bubble detectors—be it from neutrons, energetic charged particles, or a combination of both—can be compared with measurements made by other detectors, and with model calculations.

Objectives

The objective of this project is to characterize the bubble detectors (of the same type currently used aboard the ISS) and evaluate their response to high energy proton and heavy ion beams of known LET.

Approach and Methodology

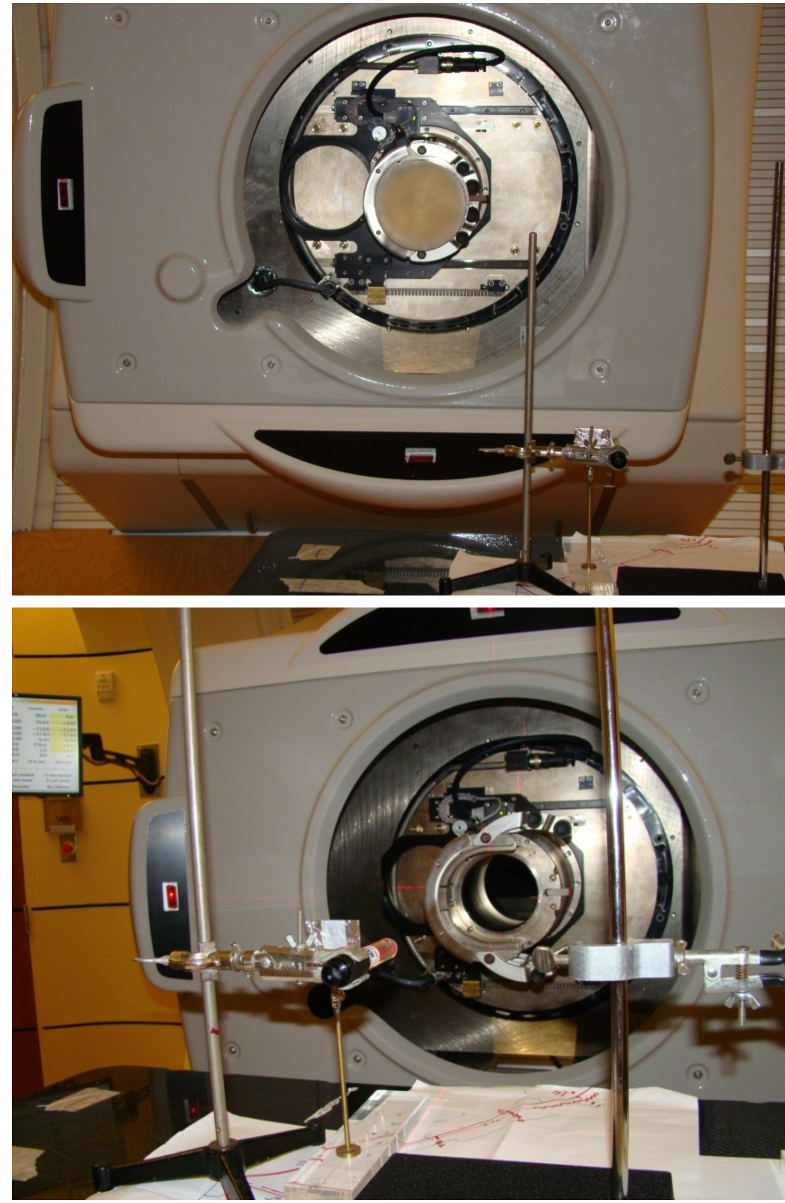
The methodology consists of:

- Exposing bubble detector to heavy ion beams of known LET at the HIMAC heavy ion accelerator at the National Institute for Radiological Sciences in Chiba, Japan
- Exposing bubble detector to protons from 30 to 230 MeV at the proton cyclotron, NIRS, Chiba, Japan, and at the ProCure proton treatment center,Oklahoma City, USA.
- Determining an “average” LET of particles above the low-LET threshold for bubble formation.

Experimental Setup

ProCure Proton Treatment Center (Oklahoma City, USA).

- The facility consists of a cyclotron that offers a large proton energy range from 60 to 230 MeV and operates at different beam intensities.
- The bubble detectors have been irradiated with proton energy of 60, 80, 162 and 226 MeV with a fluence of 0.2 to 1.3x10^8 p cm^{-2}



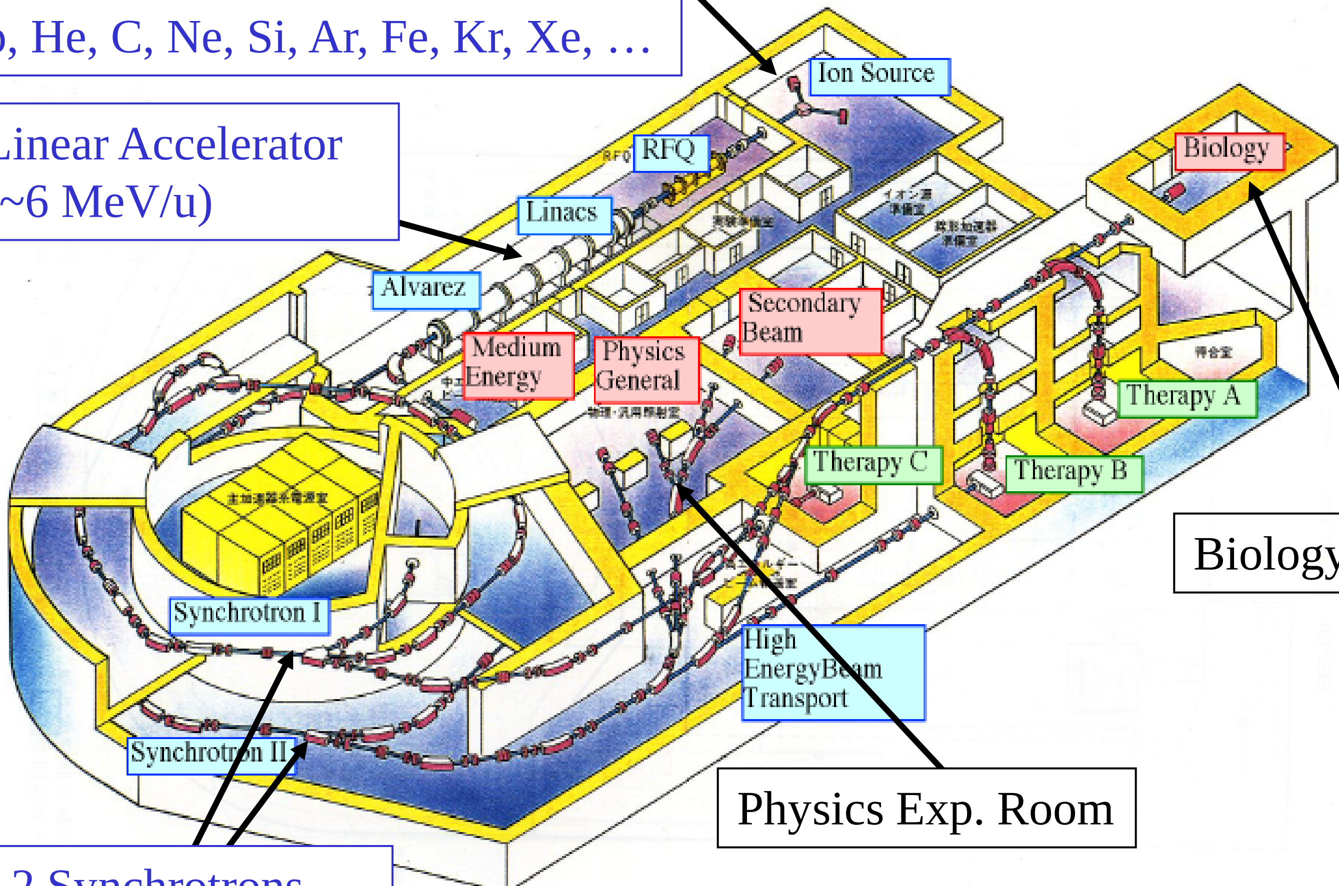
Experimental setup at the ProCure proton treatment center cyclotron

Experimental Setup

Heavy Ion Irradiations at HIMAC

Ion Source
p, He, C, Ne, Si, Ar, Fe, Kr, Xe, …

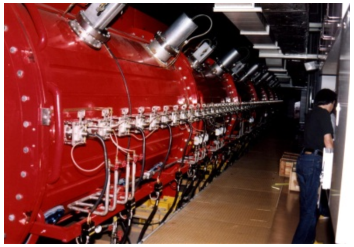
Linear Accelerator
(~6 MeV/u)



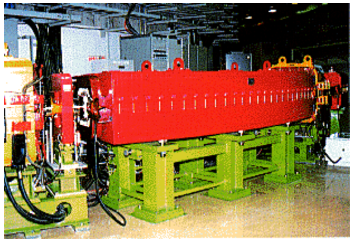
Biology Exp. Room

Physics Exp. Room

2 Synchrotrons
(125～800MeV/u)



Linear Accelerator



Synchrotron

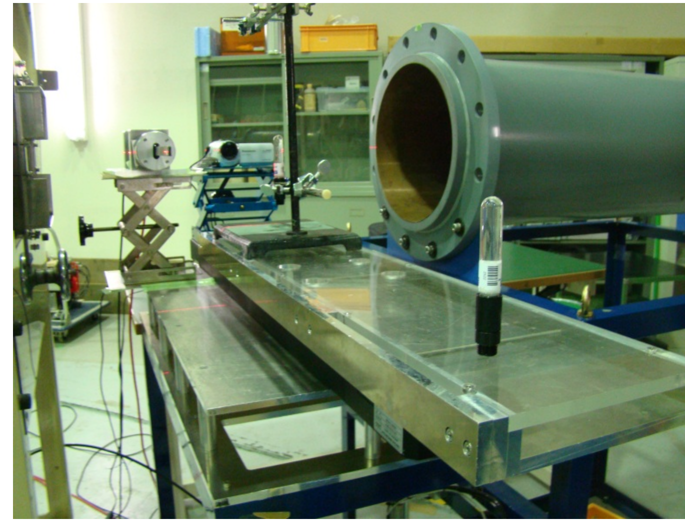
Experimental Setup

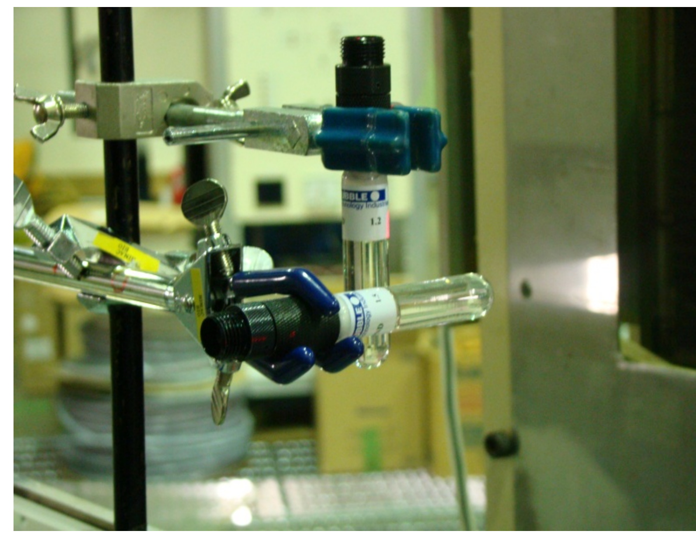
Cyclotron at NIRS, Japan

- Bubble detector was also irradiated with proton energy ranging from ~30 to 70 MeV

- The proton fluence was in the range of 0.5 to 8 x 10^6 p cm^{-2}

- Different energies have been obtained using binary filters with different thicknesses.



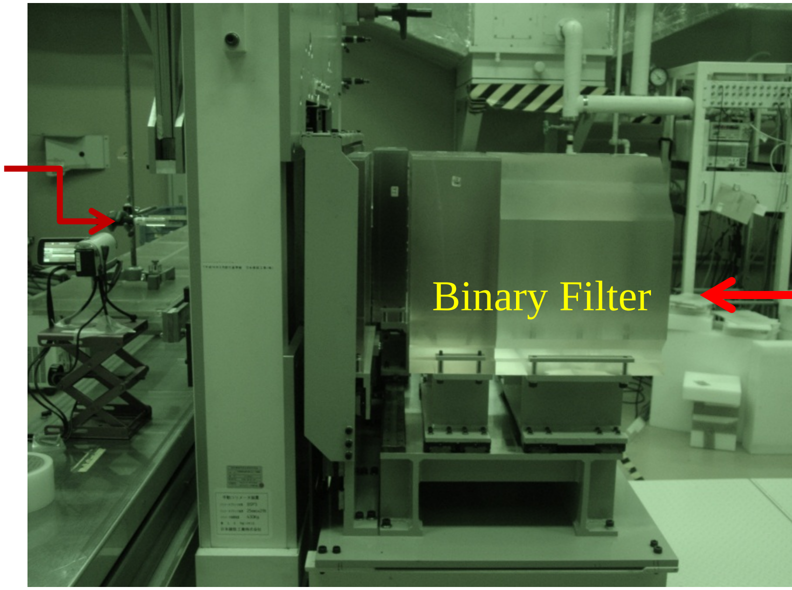


Experimental setup at NIRS Cyclotron

Experimental Setup

Heavy Ion Irradiations at HIMAC

- Bubble detector was irradiated with 3 different beam: He, Fe and Si as illustrated in Table 1.
- Different energy beams have been obtained using a binary filter (BF) with different thicknesses



HIMAC Experimental Setup at NIRS

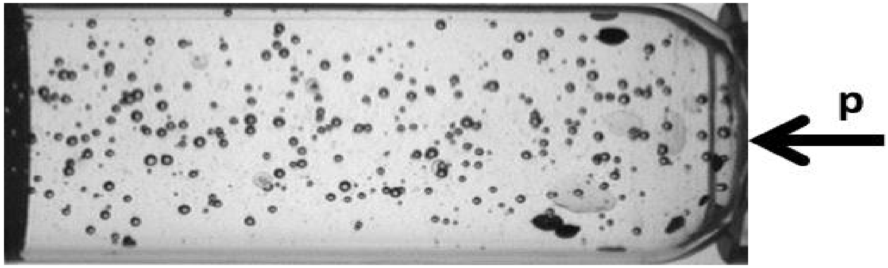
Table 1: Heavy ion beams used in characterizing bubble detector

Heavy Ion	Energy (MeV/amu)	Range (cm in H_2O)	$LET_\infty H_2O$ (keV/μm)	Fluence (particle.cm^{-2})
^{4}He	150	15.9	2.2	$4.0\div8.010^{6}$
^{28}Si	490	16.2	54.5	$0.5\div1.010^{4}$
^{56}Fe	500	9.7	186.3	$0.5\div310^{4}$

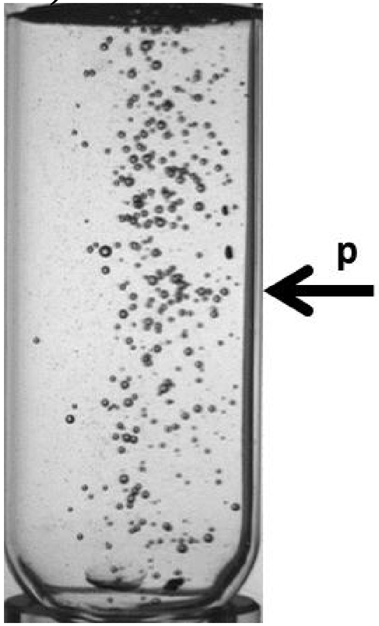
Preliminary Results

Protons

- The number of bubbles is uniform in the sensitive volume whether protons deposit their full energy in the sensitive volume of the bubble detector or not.
- There is no indication of the formation of bubbles from direct proton ionization.
- This suggests that the bubbles are formed only above certain LET threshold.



Response to 70MeV protons (protons do not deposit their full energy in the sensitive volume)

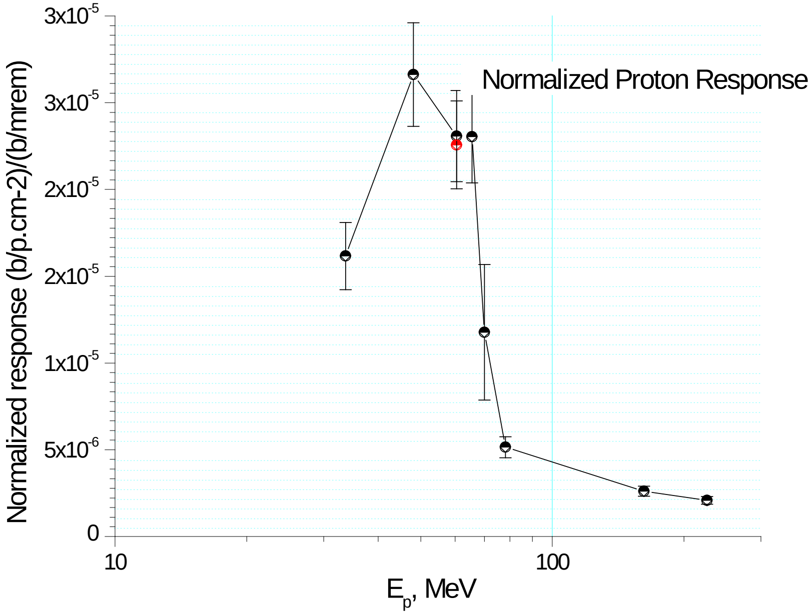


Response to 33 MeV protons (proton fully deposited its energy in the sensitive volume)

Preliminary Results

Protons

- The proton sensitivity has been evaluated from 30 to 230 MeV as shown in Figure 3.
- The Proton sensitivity behavior is similar to the neutron response of the bubble detector reported in Lewis et al. (5).



Proton response of bubble detector

Red dot on the graph is the value measured at NIRS and at ProCure proton treatment center (Oklahoma City, USA).

Preliminary Results

Heavy Ions: Si

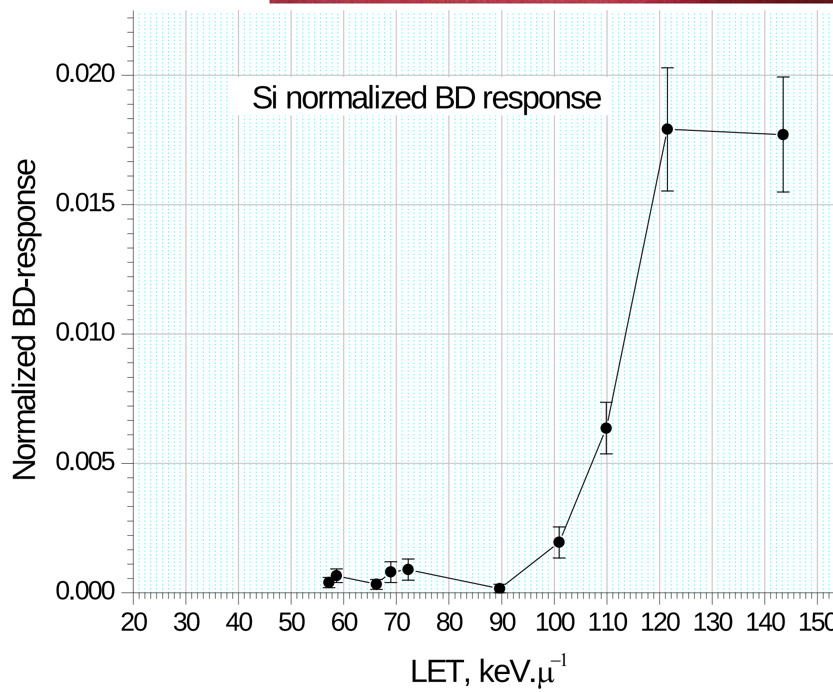
- In a series of experiments, below 100 keV/μ, there was no formed bubble in the sensitive area of the bubble detectors.

- The bubble detector response has been determined from ten experiments and normalized to neutron sensitivity as shown.

58.6keVμ^{-1}

100 keVμ^{-1}

144.5 keVμ^{-1}

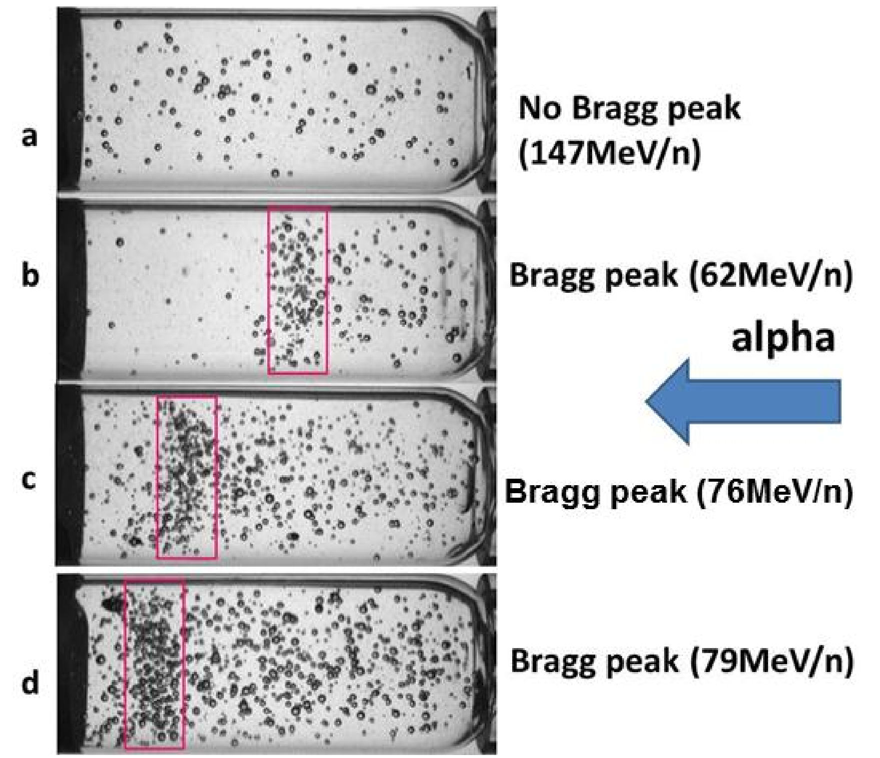


Si response of bubble detector

Preliminary Results

Heavy Ions: ^{4}He

- The results of experiments with He beam are shown.
- For alpha particles, the LET in the plateau region is not sufficient to directly create bubbles (a),
- When the range of alpha particles is less than the size of the bubble detector (Bragg peak is within the sensitive volume of the detector), the LET is sufficient to produce a visible bubbles (b, c and d)
- The processing of data is on-going to quantify the LET threshold above which bubbles are formed for He and Fe.



Results of He irradiation.

Discussion–Preliminary Results suggest the following:

- Superheated Bubble Detectors (SBD) are high-LET threshold detectors. Passage of charged particles of LET above the threshold through the sensitive volume of the detector will produce bubbles, while charged particles of LET below the threshold will not produce any visible effect in the detector.
    - Heavy charged particles with LET greater than the LET threshold will produce bubbles through direct ionization (i.e. electromagnetic rather than nuclear processes).
    - High energy (relativistic) protons, α-particles and light ions of LET below the LET threshold can only produce bubbles via nuclear reactions that yield secondary charged particles of LET above the threshold within the sensitive volume of the detector (target fragmentation).
    - Neutrons can be detected by SBD by undergoing nuclear interactions and producing secondary charged particles of LET above the threshold within the sensitive volume of the detector.
    - To a first approximation, a graph of the number of bubble in an SBD as a function of LET ought to look like a step function, with the step occurring at the threshold LET.

Discussion–Preliminary Results suggest the following:

- The number of bubbles with a unit volume of the detector scale as the incident particle fluence (and absorbed dose) up to a certain saturation threshold.
  - This threshold is dictated by the number (volume density) of superheated droplets suspended in the SBD gel (total number is 10^4 droplets per 10ml).
  - For high LET charged particles delivered in accelerator experiments, this threshold may be rather low, i.e. the passage of only a few hundred high LET charged particles through the sensitive volume of the detector may be sufficient to saturate the detector by activating a significant fraction of the superheated droplets within that volume.
  - This is less of an issue for neutrons and energetic protons and light ions due to the fact they must first undergo a nuclear interaction, the probability of which is dependent on the nuclear cross section.
  - This is also less an issue in space where the flux is considerably less than in most accelerator experiments.

Discussion–Preliminary Results suggest the following:

- It is possible that a single, long range (range > dimensions of the SBD) high LET charged particle will produce more than one bubble along its trajectory through the sensitive volume of the SBD.
    - This depends on both the size and volume distribution of superheated droplets within the SBD gel and on the radial dose distribution of the projectile.
    - In practice, it is unlikely that many instances of multiple bubbles per projectile will be observed given the small size of the droplets and their spacing.
- For the BTI space bubble detectors used in this project, the LET threshold was found to be 110 ± 10 keV/μm.
    - However, since this type of SBD contains a stiffer gel than that of other SBD, the threshold of other SBD may well be lower.
    - If the LET threshold does depend on gel stiffness, it might form the basis of a crude LET spectrometer.

Discussion–Preliminary Results suggest the following:

- The SBD provides a single, integrated scalar quantity: number of bubbles per unit volume.
    - This number is proportional to the fluence of charged particles with LET above the bubble formation threshold.
    - Absorbed dose (and dose equivalent) are proportional to both fluence and LET.
    - The number of bubbles per unit volume is proportional to LET in only a binary way.
    - Thus, bubble density can provide fluence of charged particles (both primary and secondary) above the LET threshold, but provides no information about the LET spectrum.
- The determination of absorbed dose or dose equivalent based on bubble number for SBD exposed in highly complex and mixed radiation fields like those encountered in space is difficult and requires additional information, either from measurements made by other instruments or from model calculations.

Planned Work

We are planning to:

- Carry experiments at NIRS with Oxygen and Carbon beams, 400 and 290 MeV/amu, respectively at HIMAC early next year.
- Complete Fe and He data processing and confirm the LET threshold above which the bubbles are formed.
- Determine an “average” LET of particles above the low-LET threshold based on model calculations, both previous and carried out as part of this work, and from previous dosimetric measurements made aboard spacecraft.
- This value will be used in determining conversion coefficients to covert the number of bubbles observed in bubble detectors exposed in space into high-LET absorbed dose and dose equivalent values.

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