Response of Space Bubble Detectors to Heavy Charged Particles

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Introduction

- Bubble detectors have been flown aboard the International Space Station (ISS) in several missions to measure the neutron contribution to total ionizing radiation dose equivalent received during space flights.
- The data measured by the bubble detector so far has been reported as a neutron reading of the device.
- A systematic study of the bubble detector response to heavy charged particles and high energy neutrons has been on going since 2012.
- In our previous WRMISS meeting we have reported the bubble detector response to high energy protons from 30 to 230 MeV protons as well as a correction calibration factor to high energy neutrons (measured at LOS Alamos National Laboratory, USA).
- At that time we concluded that bubble detectors are high-LET threshold detectors. The passage of charged particles of LET above the threshold (**LET_{min}**) 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.
- The **LET_{min}** may depend on the charged **Z** of the ion.

Objectives of the current work

1. Determine the minimum LET_{min} required to form a bubble in the bubble detector.
2. Investigate the Z-dependence of LET_{min}

Experimental Setup and Facilities

Space Bubble Detector and Reader

- The bubble detectors used in these experiments were Space-Type Bubble Detector of the same type used aboard the International Space Station.

- The bubble counting was done automatically using a BDR-II bubble detector reader as shown in Fig.1

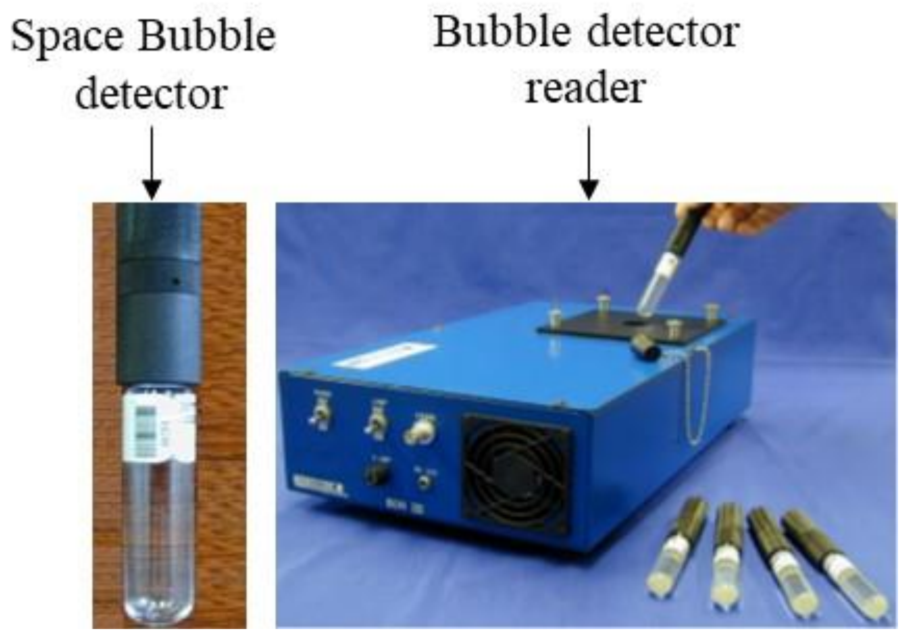


Fig. 1: Bubble Detector Reader

Experimental Setup and Facilities _ continued

HIMAC Facility

- For heavy ions, all exposures were conducted in the HIMAC BIO Room.
- Bubble detectors were exposed to 10 cm diameter of different heavy ion beams at different energies (along the beam).
- The Bragg peak for each ion was positioned inside the sensitive volume of the detector using layers of water equivalent absorber with thicknesses ranging from 0 to ~20 cm.
- At lower beam intensities, a 1 cm^2 plastic scintillator was placed in the beam line, and the output of the scintillator was integrated by a scaler set to interrupt the beam when a present fluence had been achieved.

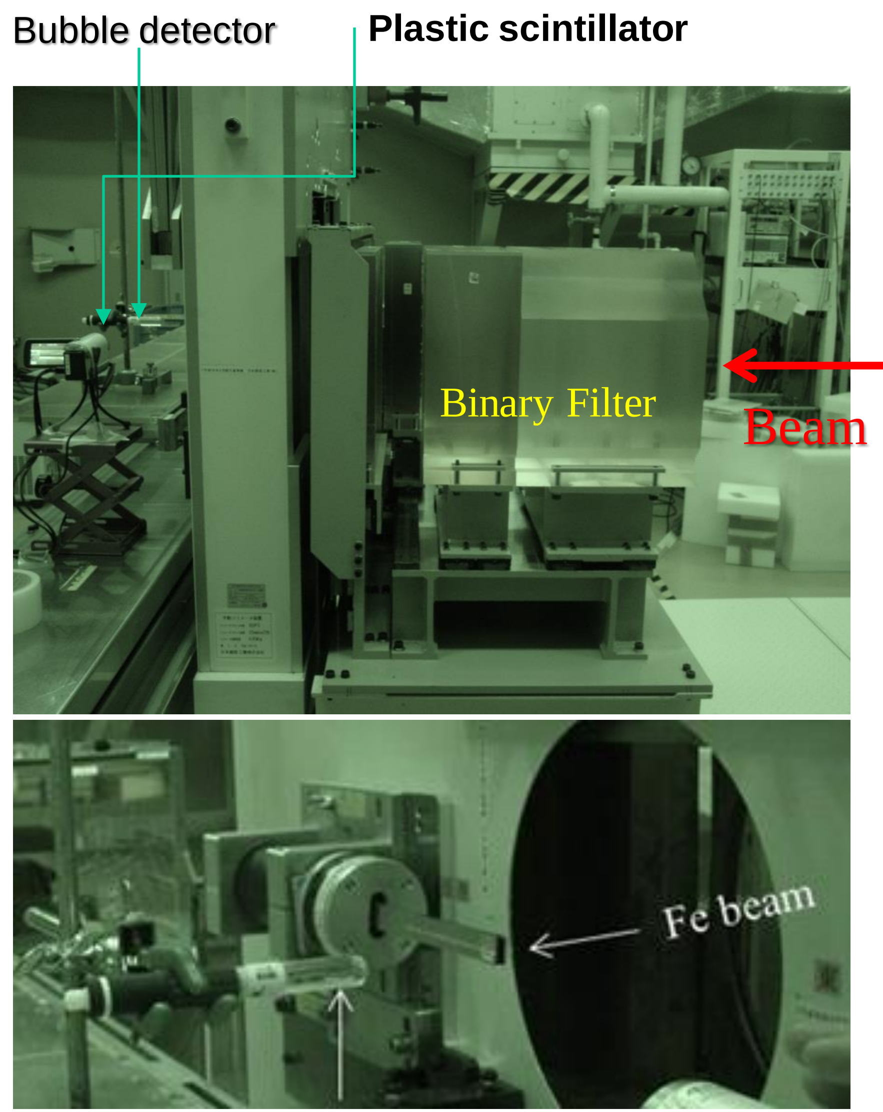


Fig.2: Experimental Setup at HIMAC-NIRS

Experimental Setup and Facilities _ continued

Beam Characteristics

- Bubble detectors were irradiated either individually or in a set of 2-3 detectors.

- The LET was determined at the beginning of the Bragg peak of each ion in different experiments indicating the minimum LET_{min} required to form a bubble in the bubble detector.

- The value of LET_{min} was determined for each ion examined (see below).

Characteristics of the used heavy ion beams

Ion	Energy MeV/n	Range, cm in H_2O	$LET_\infty H_2O$ keV/μm	Fluence particles/cm²
${}^{4}_{2}He$	150	15.9	2.2	4.0 – 8.0 x 10^6
${}^{12}_{6}C$	400	27.4	11.1	0.8 – 9.2 x 10^5
${}^{16}_{8}O$	400	20.6	19.6	0.7 –1.2 x 10^6
${}^{28}_{14}Si$	490	16.2	54.5	0.5 – 1.0 x 10^4
${}^{20}_{10}Ne$	400	16.4	30.6	1.02 – 1.53 x 10^5
${}^{56}_{26}Fe$	500	9.7	186.3	0.5 – 3.0 x 10^4

Results

Helium and Proton Beams

- During the proton exposure, the number of bubbles is uniform in the sensitive volume whether protons deposit their full energy in the sensitive volume or not.

- The lack of the Bragg peak indicates that there is no formation of bubbles from direct proton interaction (ionization) i.e. the bubbles are formed only above certain LET threshold.

- Bubble detectors were exposed to a 150 MeV/n He beams (15.4 cm range and $LET_{\infty}H_2O$ 2.2 keV/μm).
- At 150 MeV/n, the Bragg peak lies beyond the dimensions of the detector length. This LET is not sufficiently large to produce bubbles by direct ionization. However, bubbles can be created by helium ions undergoing nuclear interactions with the heavy nuclei in the active volume and such nuclear interactions account for the relatively uniform distribution of bubbles seen with 2.2 keV/μm
- Unlike protons, 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 enough to produce a visible bubbles

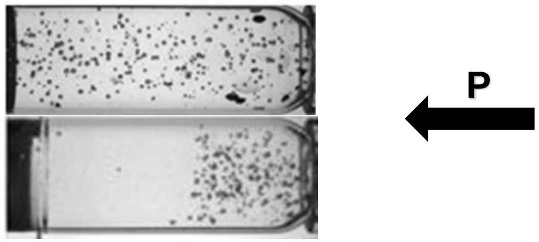


Fig.3: Proton of 70 and 49.8 MeV

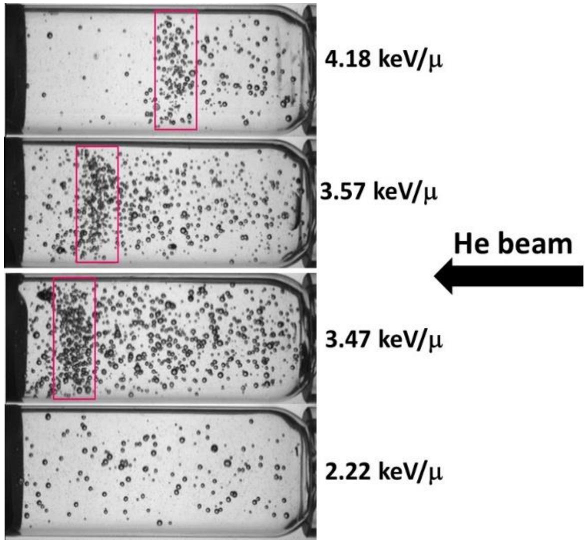


Fig.4: Helium beam exposures

Results_ Continued

Oxygen and Carbon Beams

- The experiment with Oxygen beam without any absorber are shown in Fig5.d. With no absorber (19.6 keV/μm), the range of the Oxygen particles is beyond the length of the detector (4.5 cm).
- Fig.5 a, b, c illustrate results from different LET exposures using different thicknesses of the absorber. The concentration of the bubbles at the Bragg peak is much larger than in the plateau region demonstrating that the LET in the Bragg peak is large enough to form bubbles through direct interaction (ionization).
- Fig.6 shows the bubble detector images for three different exposures with Carbon beams. The Bragg peak in Fig.6a and b appears at different depths within the detector sensitive volume. The population of bubbles is much larger in the Bragg peak region as compared to the plateau. One can notice that a comparison of the Bragg peak position in both Fig.5 and 6 show that the value of the LET threshold for bubble formation is slightly different for the two beams.
- This difference in minimum LET threshold for bubble formation by beams of different Z is consistent in different experiments.

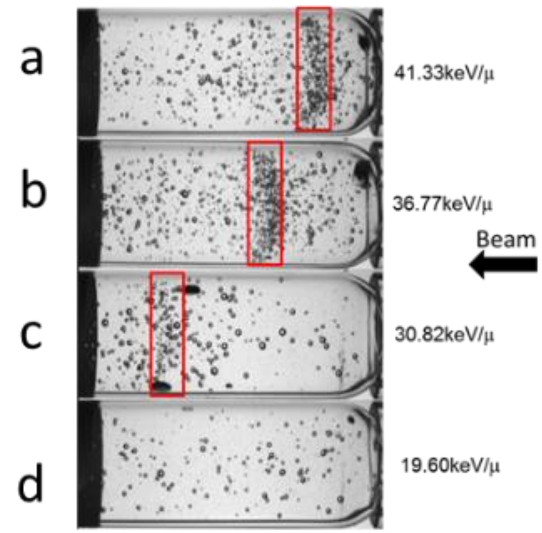


Fig.5: Oxygen beams

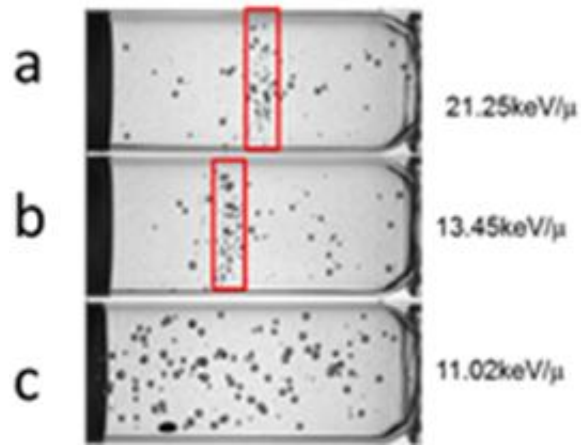


Fig.6: Carbon beams

Results_ Continued

Silicon and Neon

- In a series of experiments with Si beams, below 100 keV/m, there was no formed bubbles in the sensitive area of the BD (see Fig.7c).
- The bubble detector response has been determined from 10 experiments and the LET minimum has been determined (see later).
- Similarly, the bubble detector has been exposed to to Ne ion beams. Five sessions have been carried out with different energies.
- Unlike protons and light charged particles (He, O and C), Ne, and Si beams were ideal beams since the formation of the bubble is mainly due to the ionization process.
- We have not observed any significant number of bubbles in the plateau region of the Bragg curve since the LET is below the minimum LET_{min}.

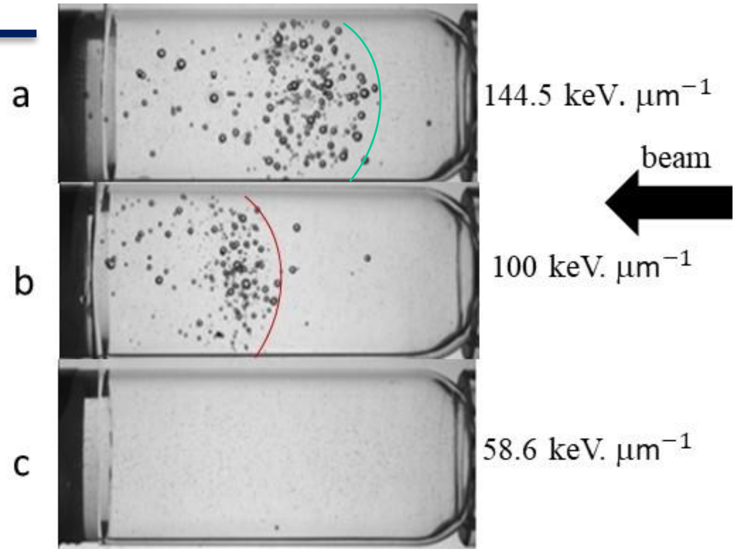


Fig.7: Si Beams

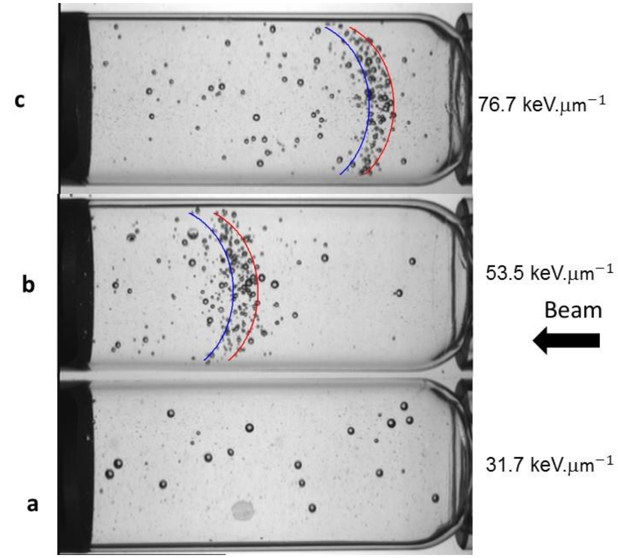


Fig.8: Ne Beams

Results_ Continued

Iron Beam

- The energy of the Fe beam without any binary filter is 421 MeV/n. The $LET_{\infty}H_2O$ of such beam is 201.7 keV/μm and a range of 7.4 cm in water.

- With a 201.7keV/μm, Fig.9a shows that the distribution of the formed bubbles is uniform along the beam.

- In three other different experiments of 260.5, 276.6, and 297keV/μm shown in Fig.9 b, c, and d, the Fe particles deposit their full energy within the sensitive volume of the detector, but the number of bubbles is uniform, and no significant increase in the number of bubbles within the Bragg peak region is observed since the LET is enough to create bubble by direct ionisation from the beginning of the detector.

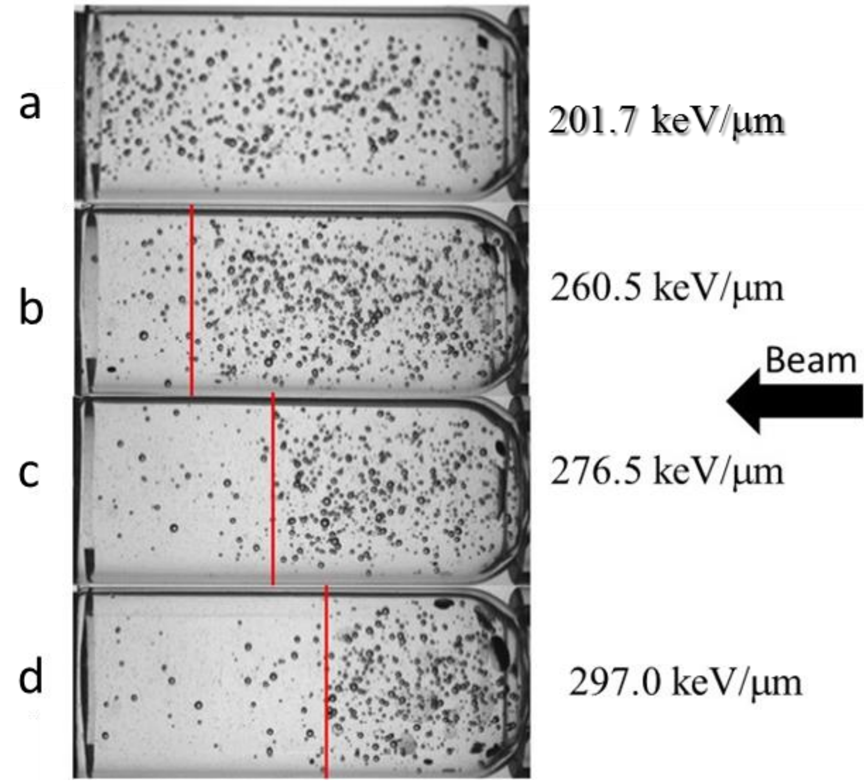


Fig.9: Fe Beams

Results_ Continued

Z- dependence of LET threshold

- The measured data from all previous experiments have been analyzed for each ion examined and the results are presents in Fig10.
- The LET required for bubble formation appears to increase with increasing ion charge Z.
- Similar experiments performed using N and Ar ions have been added to Fig. 10 and appear to fit the trend of the current results.
- The trend of the LET threshold dependence on Z may be related to the ion track structure. It is expected that the threshold for bubble formation should be determined by the deposited energy density or ionization density along an ion track which is not fully described by the parameter LET_∞ alone.
- For higher Z, the delta rays density is smaller and an increase in the LET to form the bubble is required to compensate for the lower density of the delta rays.

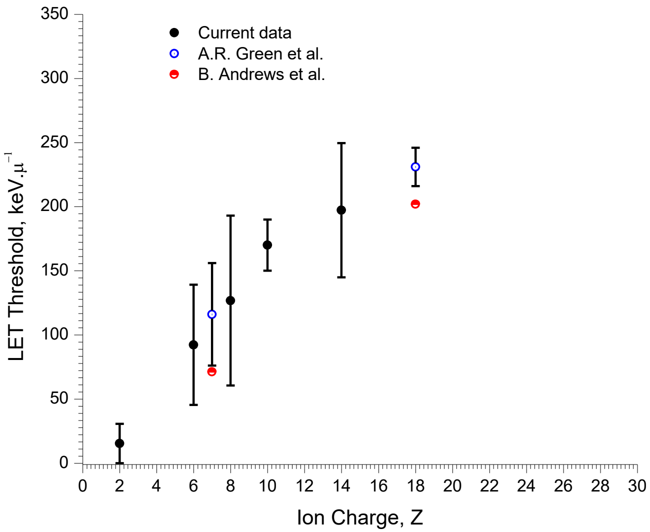


Fig.10: Z-dependence of LET threshold

Results_ Continued

Comments on the response functions to heavy ions

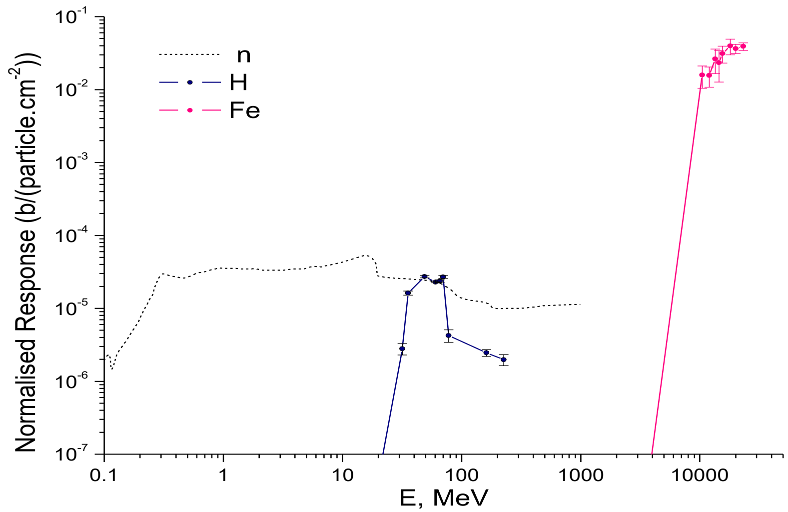
- The evaluation of the contribution of charged particles to the bubble detector reading can made only in a unit of bubble but not in unit of dose equivalent.
- Bubble detectors are sensitive to charged particles and such sensitivity varies from one ion to another as a function of Z as well as a function of energy.
- The contribution of charged particles to the bubble detector reading strongly depends on the flux, the corresponding sensitivity of the charged particle and Z of the projectile.
- For instance the sensitivity to Iron is much more than the sensitivity to protons, but the over all contribution would be much lower due to the lower flux of Fe particles.
- The determination of the response function of each the measured ion is ongoing and data will be reported in WRMISS24

$$\mathit{bubbles\ produced\ in\ radiation\ field} = \sum_i \int_0^\infty R_i(E)\cdot\Phi(E)\,dE$$

R – reponse function

Φ– is the fluence of a radiation type

E – is the energy



Neutron, proton and preliminary Fe response functions

Concluding Remarks

As part of the systematic study of the space bubble detectors response to heavy charged particles, experiments have been conducted with five heavy ions at the NIRS HIMAC heavy ion accelerator. The results obtained has led to the following conclusion:

- The study confirmed our previous conclusion that Bubble Detectors are high-LET threshold detectors.
- Heavy charged particles with LET greater than the LET threshold 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.
- With five different ions beams, for the space bubble detectors used in this study, the minimum LET_{min} threshold was found to be depending on the atomic number of the projectile charged particle, Z and the LET_{min} increases in a nonlinear fashion with increasing Z.

Some References

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