Radiation fields from HZE particles studied with Geant4-based simulations

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FAIRNESS, Berlin, 15-21 September 2013

Apollo 11

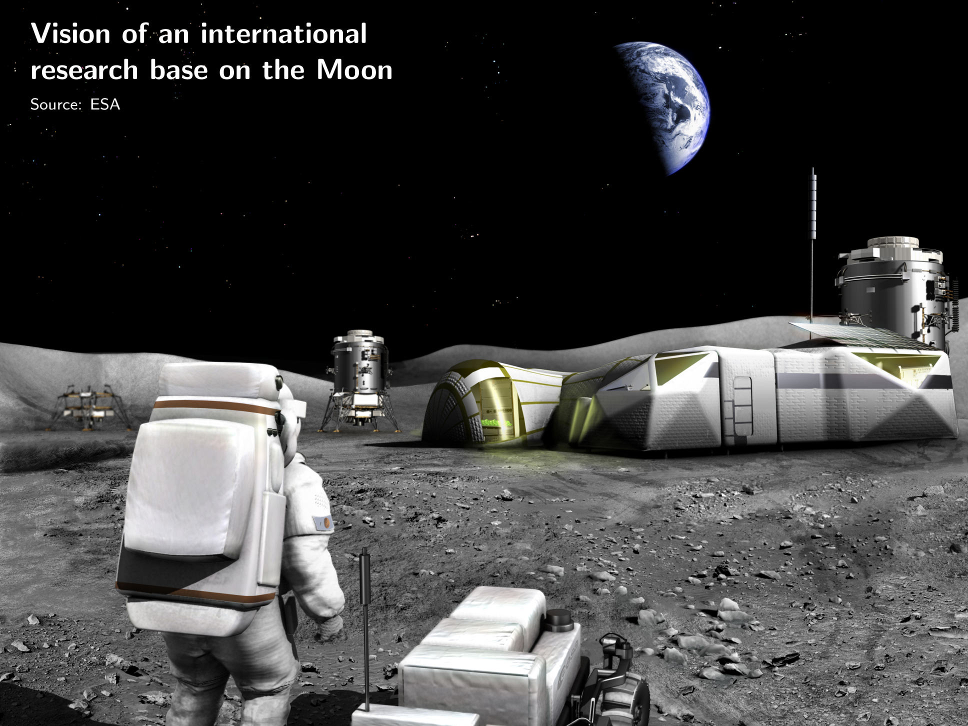
Source: NASA

20 Jul. 1969

Edwin E. Aldrin Jr.

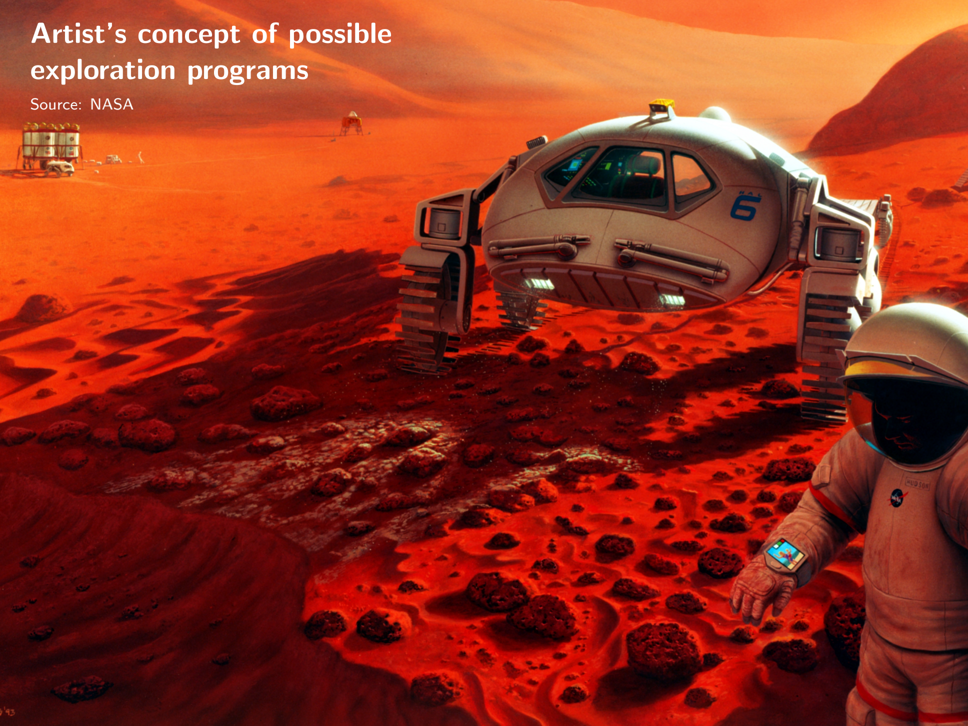
Vision of an international research base on the Moon

Source: ESA



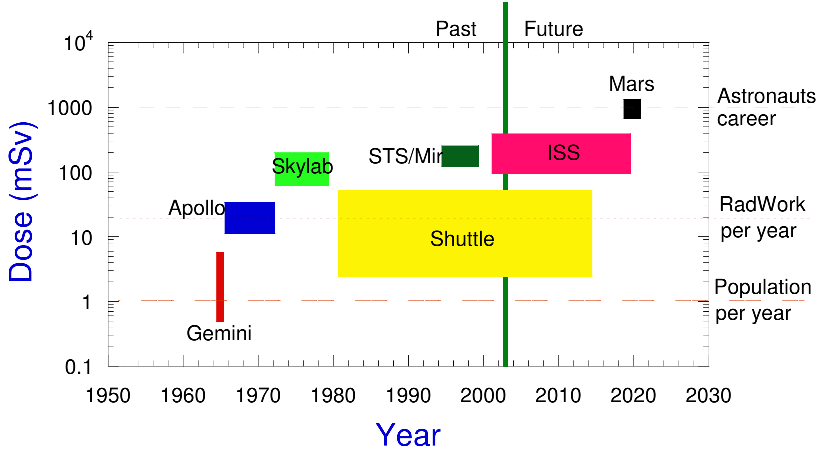
Artist’s concept of possible exploration programs

Source: NASA

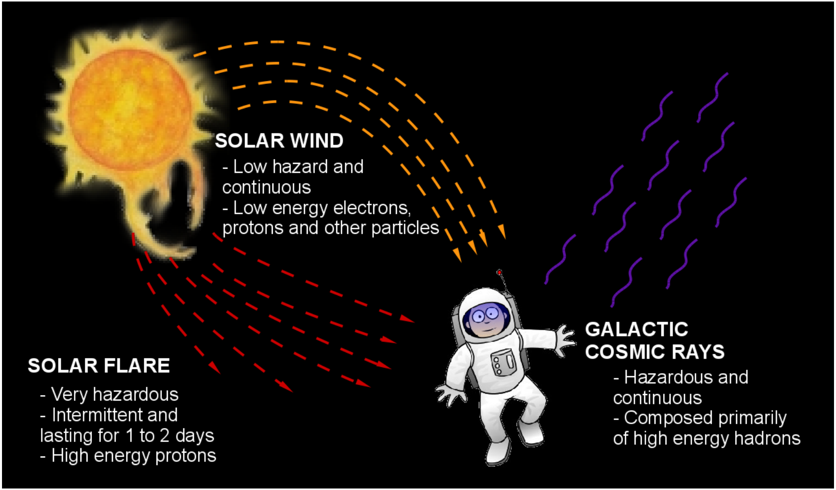


Source: Sihver

Total effective dose in different missions



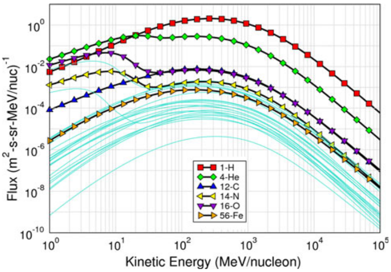
Radiation Environment in Deep Space



Source: adapted from NSBRI

Galactic Cosmic Rays (GCR) are the main concern for manned missions in deep space.

Galactic Cosmic Rays



Source: A. Keating *et al.*, 2012

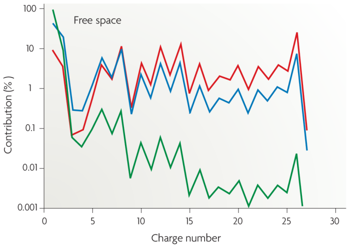


Figure 1 | **Space radiation environment and shielding.** The contribution in fluence (green), dose (blue), and dose equivalent (red) of different nuclei in galactic cosmic radiation.

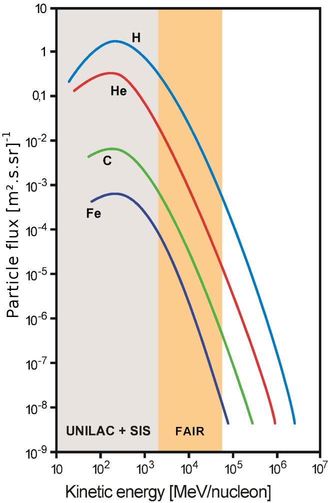
Source: M. Durante and F. Cucinotta, 2008

Detected particles from GCR consist of 83% protons, 14% helium and 1% heavier nuclei. The maximum of the spectrum for specific nuclei is between 100-1000 MeV/u.

Several ions contribute differently to absorbed dose. Shielding is a problem due to high charge high energy (HZE) particles.

Space Research at FAIR

Future research at FAIR shall reduce uncertainties on radiation effects due to HZE particles.

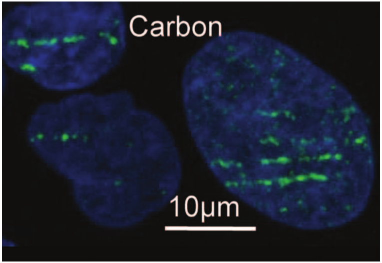


Source: GSI

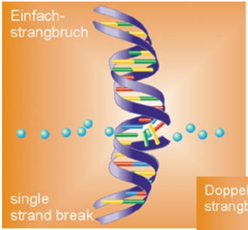
Radiation Effects by Ions

Better understanding of radiation effects due to ion tracks are required for future interplanetary human missions.

9.5 MeV/u ^{12}C by in-beam microscopy.

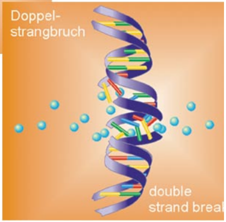


Source: B. Jakob *et al.*, 2009



Single strand breaks are usually repaired by the cell.

It is more difficult to repair double and multiple strand breaks.

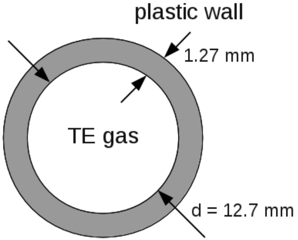


Energy imparted to tissue per unit of track length on scale of micrometres and nanometres matters to the biological action of radiation.

Microdosimetry Technique

Patterns of energy deposition on micrometer scale are measured by means of a Tissue-Equivalent Proportional Counter (TEPC).

Scheme of a typical walled TEPC



TEPC: a plastic sphere filled with low-pressure gas, equivalent to a few μm sphere of tissue, an object of a cell nucleus size.

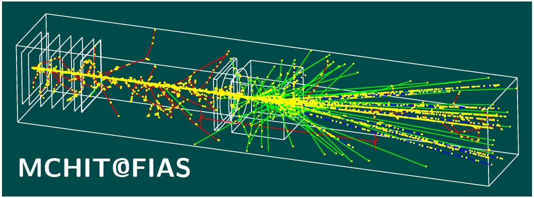
Lineal energy: $y = \varepsilon/\bar{l}$
ε: energy deposited in the TEPC
$\bar{l} = \frac{2}{3}d$: mean chord length

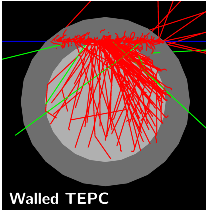
TEPC is commonly flown on the ISS. TEPC is also applied for investigation of radiation effects at ground-based facilities.

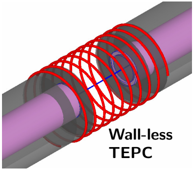
Monte Carlo simulations can be applied to investigate different scenarios of particle/energy/target in space.

Monte Carlo Model for Investigation of Radiation Effects

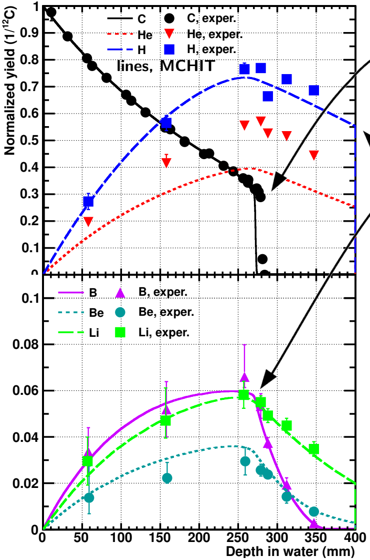
- The Monte Carlo model for Heavy-Ion Therapy (MCHIT) was developed at FIAS for benchmarking of Geant4 models to experimental data relevant to ion beam cancer therapy.
- MCHIT was extended for benchmarking of models to experimental data relevant to space research as well.
- Detailed implementation of TEPCs are applied for simulation of microdosimetric data for HZE particles.







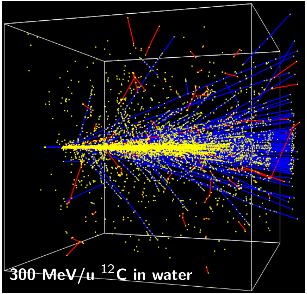
Yield of Secondary Fragments



Exp. data: E. Haettner *et al.*, 2006

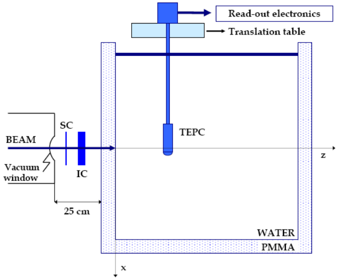
- Up to 70% of 400 MeV/u ^{12}C nuclei are fragmented.
- Secondary fragments are created, from protons till boron with various radiobiological properties.

A lot of work for nuclear fragmentation models!

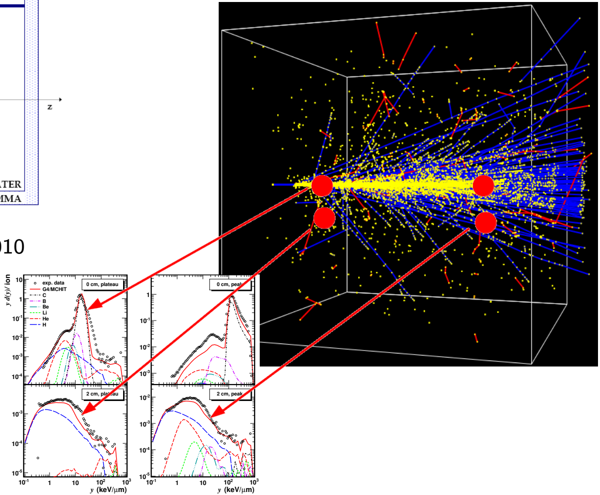


TEPC Measurements at Several Positions at GSI (I)

Irradiation by 185 MeV/u ^{7}Li and 300 MeV/u ^{12}C pencil-like beams.



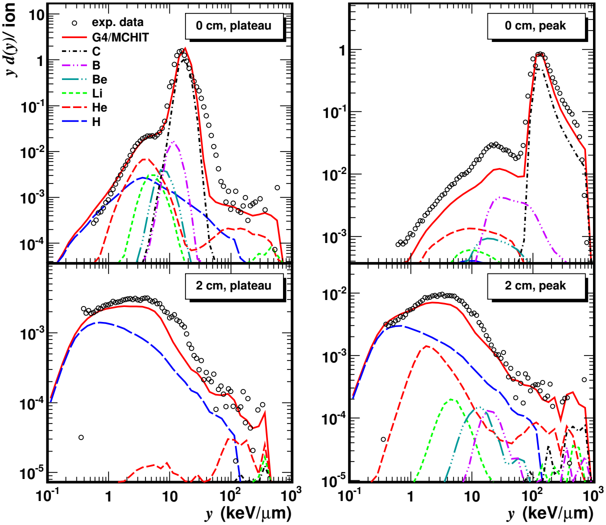
Source: G. Martino *et al.*, 2010



TEPC Measurements at Several Positions at GSI (II)

- Spectra on beam axis are mainly due to primary ion and heavy fragments.
- At 2 cm away from the beam axis the spectra are mainly due to light fragments.

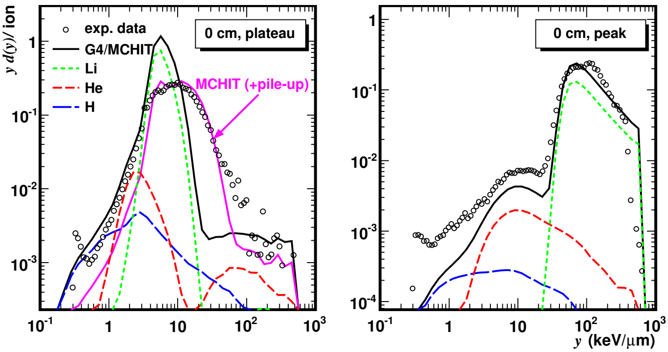
^{12}C 300 MeV/u



Source: L. Burigo *et al.*, 2013

TEPC Measurements at Several Positions at GSI (III)

^{7}Li 185 MeV/u

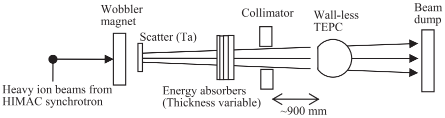


- Results of simulations agree with experimental data at "0 cm, plateau" when pile-up of events is taken into account.

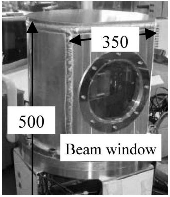
Source: L. Burigo *et al.*, 2013

Microdosimetry with Wall-Less TEPC at HIMAC (I)

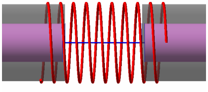
Wall-less TEPC behind a range shifter irradiated by H, He and Si ions.



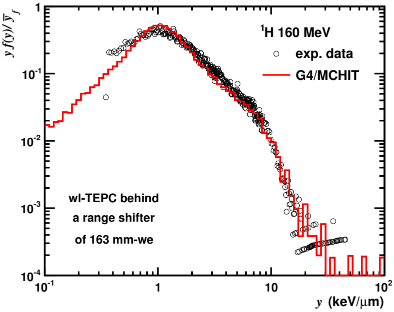
Wall-less TEPC behind a rage shifter. Measurements are sensitive to nuclear reactions.



Source: S. Tsuda *et al.*, 2012



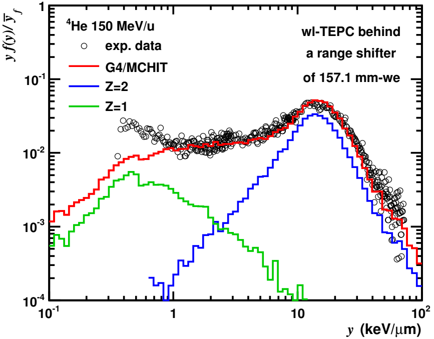
Internal geometry of wl-TEPC in MCHIT



- Calculated microdosimetric spectra for protons behind a range shifter with wall-less TEPC agree well with experimental data.

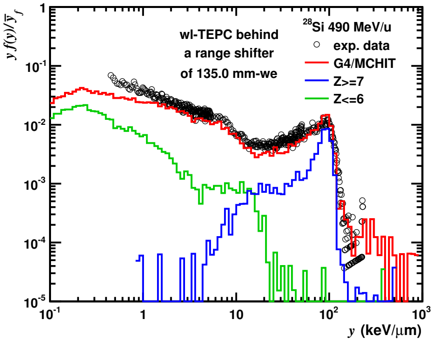
Source: L. Burigo *et al.*, 2013

Microdosimetry with Wall-Less TEPC at HIMAC (II)



- Fragments with higher nuclear charge contribute mainly at large-y events.

- Microdosimetric spectra for helium and silicon ions are well described by G4/MCHIT.



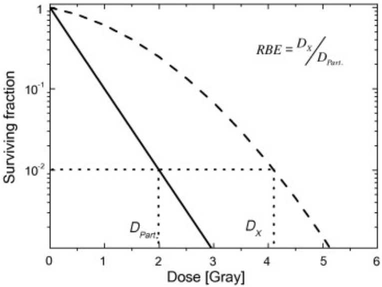
Source: L. Burigo *et al.*, 2013

Estimation of Radiation Effects by Ions (I)

The survival fraction S of cells can be expressed as

$$S = \exp\left[-\alpha D - \beta D^2\right],$$

where D is the delivered dose and α and β are parameters.



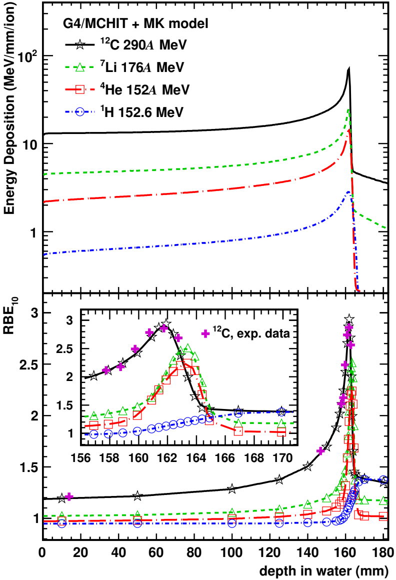
Source: M. Beuve *et al.*, 2009

The Relative Biological Effectiveness (RBE) can be estimated using the Microdosimetric-Kinetic (MK) model (Hawkins 2003, Kase et al. 2006)

$$RBE_{10} = \frac{2\beta D_{10,R}}{\sqrt{\alpha^2 - 4\beta \ln(0.1)} - \alpha} \qquad \alpha = \alpha_0 + \frac{\beta}{\rho\pi r_d^2} y^*$$

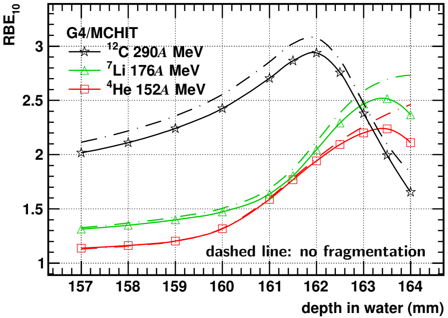
y^* **is calculated from the microdosimetry spectrum.**

Estimation of Radiation Effects by Ions (II)



Source: L. Burigo *et al.*, 2013

- G4/MCHIT+MK model can be used to estimate RBE for light ions.



- The fragmentation of ions may reduce the RBE by 10% at the Bragg peak.

Conclusions

- Methods used to simulate detectors in nuclear and particle physics experiments are also successful for calculation of patterns of energy deposition on micrometre scale.
- With G4/MCHIT model one can calculate microdosimetric data for many ions and beam energies relevant for ion beam cancer therapy and space research.
- Measurements with TEPC inside or behind a phantom impose a challenge for hadronic models. Geant4 models are able to describe reasonably well microdosimetric spectra in the presence of nuclear fragmentation reactions.
- G4/MCHIT coupled with MK model can be used for estimation of RBE for light ions.

Thank you for your attention!

Thanks to the organizing committee.

I am grateful to Beilstein Institute and HGS-HIRe for the support.

Many thanks to

Igor Mishustin
Igor Pshenichnov
Marcus Bleicher