GEANT 4 simulation of the Helios cosmic ray telescope E6:
Feasibility of chemical composition studies

J Marquardt, B Heber, M Hörlöck, P Kühl, R F Wimmer-Schweingruber
Christian-Albrechts-Universität zu Kiel

Abstract. In October 2011, ESA announced the selection of Solar Orbiter as one of the Cosmic Vision M missions. It’s launch is foreseen in 2018. Therefore it is worthwhile to revisit the energetic particle measurements together with the solar wind and magnetic field data from Helios in light of better theoretical understanding and advanced analysis and modelling techniques developed during the past 20 years. In this contribution we will present a GEANT 4 simulation of the response function of the Helios E6 experiment, that measured electrons in the energy range from a few 100 keV to above 10 MeV, ions from 1 MeV/nucleon to above 50 MeV/nucleon, and its application to the data analysis with respect to the chemical composition of the Galactic Cosmic Rays.

1. Introduction
The elemental composition of the cosmic rays in the heliosphere has been measured a number of times during different phases in the solar cycle [1; 2] and different radial distances from the Sun beyond the Earth orbit[e.g. 3; 4].

One of these measurements was carried out by the Experiment 6 (E6) on Helios. Helios 1 and Helios 2 were launched on December 10, 1974 and January 15, 1976, respectively. The two almost identical space probes were sent into ecliptic orbits around the Sun. The orbital period around the Sun was 190 days for Helios 1 and 185 days for Helios 2. Their perihelia were 0.3095 AU and 0.290 AU, respectively.

The E6 particle telescope relies on the \( \frac{dE}{dx} - E \)-method [see e.g. 5]. In order to interpret the measured data a detailed understanding of the instrument is needed and can be obtained by modelling the physical processes inside the detector taking into account the instrument geometry as well as environment. [e.g. 6].

The instrument consists of a stack of 5 semiconductor, a sapphire and a plastic scintillation detector (see Fig. 1), which measures the number of particles hitting each detector and their energy losses. A rough particle identification (species, energy and incoming direction) can be obtained by analyzing the count rate data that are obtained in (anti)-coincidence of a set of active detectors [see 7]. For a statistical ensemble not only the (anti-)coincidence conditions but also the energy loss in the last three detectors are known. The channel that is analyzed here in detail counts particles in the energy range from \( \sim 13 \) MeV/nucleon to \( \sim 27 \) MeV/nucleon protons and helium.

In order to determine the chemical composition of cosmic rays, the detailed instrument response for different particle species is calculated utilizing a newly developed model of the E6 instrument. The calculations are based on the program library Geant4 that is a toolkit for the simulation of the passage of particles through matter [8]. The purpose of this contribution is to show that the Helios E6-Experiment is capable of determining the chemical composition of particles that are stopped in the detector sensor up to
Table 1. Relative Elemental Abundances at 160 MeV/Nucleon from ACE/CRIS [2; 9]

| Element | Solar Minimum 1997/1998 [2] | Solar Minimum 2009-2010 [9] | Solar Maximum 1998-2001 [2] |
|---------|-----------------------------|-----------------------------|-----------------------------|
| B       | 1803.8 ± 10.4               | 1725.7 ± 19.4               | 1986.4 ± 11.3               |
| C       | 7337.0 ± 18.4               | 7235.4 ± 45                 | 6780.2 ± 18.4               |
| N       | 1713.7 ± 8.4                | 1678.9 ± 12.3               | 1836.1 ± 9                  |
| O       | 7082.6 ± 16                 | 7137.0 ± 42.7               | 6520.6 ± 15.6               |
| Ne      | 998.7 ± 5.6                 | 998.9 ± 8.4                 | 1050 ± 5.8                  |
| Mg      | 1368 ± 6.1                  | 1375.3 ± 10.3               | 1367.3 ± 6                  |
| Si      | 1000 ± 5                    | 1000 ± 7.8                  | 1000 ± 4.8                  |

silicon. The chemical abundances of some light elements at 1 AU known from literature are summarized in Tab. 1.

2. Instrumentation

The Kiel experiment E6 for studying energetic cosmic rays was built as an universal detector. It was supposed to measure most effects of the cosmic radiation which occur in interplanetary space. The energy range extends from 1.3 MeV/n to >1000 MeV/n for nuclei and from approximately 0.3 to 8 MeV for electrons. The on-board data processing system evaluates the measured pulses created during the particle transition.

Figure 1. Schematic of the Helios E6

The detector system consists of five semiconductor-detectors of increasing thickness that are shown in Fig. 1. The figure also indicates the thicknesses of the detectors. While detectors D1(A) and D2(B) are silicon-surface-barrier-detectors with a thickness of 100 and 1000 µm, the other three are lithium drifted detectors with a thickness of 3000 µm. The first two (D1 and D2) are used for the determination of the lowest energy channels, for the definition of the geometry factor for stopping particles (energy ranges below 51 MeV/N) as well as for the discrimination between electrons and nuclei. The first detector does not respond to relativistic electrons (above 300 keV), the discrimination between electrons and nuclei is
that the first detector is not triggered for electrons. To avoid false identifications by these discrimination
conditions, the first and second detectors have been placed on top of each other, as close as possible.
Charged particles, which penetrate the fifth detector and the aluminum absorber beneath, are detected
in the Sapphire-Cerenkov-detector. The Cerenkov-threshold for this material ($n = 1.8$) is $E_s = 210$
MeV/nucleon. Because the Sapphire-Cerenkov-detector also delivers scintillation light, particles in the
energy range above 51 MeV/nucleon are counted in an integral channel.

3. Data Analysis
In order to determine the chemical and the isotopic abundance together with the energy spectra of each
species it is common to design a detector telescope based on a stack of detectors that are surrounded
by an anticoincidence detector. The characteristics for stopping particles can then be determined by the
$\Delta E \cdot E_0$ method [e.g., McDonald and Ludwig 5]. The principle of this method shall be explained by
means of the left panel of Fig. 2. A charged particle with the energy $E_0$ penetrates the thin first detector

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Left: Sample particle trajectory in a dE/dx-E-telescope. Right: $\Delta E \cdot E_0$ versus $E_0/\Delta E$-
distribution for (from the bottom to the top) protons, helium, C, N, O, Ne and Si using the energy loss
$\Delta E$ of the first detector and the sum of the measured energy losses in the first three detectors as $E_0$. The
entries below the curves are caused by the non uniformity of first detector (for details see text).
}
\end{figure}

D1 and stops in the thick detector D2. In the first detector, with a thickness of $\Delta x$, the particle loses the
energy $\Delta E$ by ionization. The residual energy $E'$ is deposited in the second detector. The entire kinetic
energy $E_0$ results from the sum of $\Delta E$ and $E'$, the energy losses in both detectors. From the Bethe-Bloch
relation [5], the energy loss in both detectors can be determined for a known detector material and for
particles of a known species. If $\Delta E = dE/dx \cdot \delta x \ll E'$ and for non-relativistic particles of mass $M$ with
$E = \frac{1}{2} M v^2$ we obtain the following relation:

\[ \Delta E \cdot E_0 \propto Z^2 \cdot M = const. \]  

This constitutes a typical quantity for a particle-species. Since $Z$ and $M$ can only take discrete values,
the relation offers a possibility to separate various particles, i.e., in addition to their energy, to determine
their mass and nuclear charge. However, note that $\Delta E$ may vary due to the statistical variation of the
ionization and because of the different path-lengths, $\Delta x$, due to the opening angle of the telescope. Thus
in order to separate different isotopes from each other the path-length variations have to be minimized.
The concept of the $\Delta E \cdot E_0$ is best realized for particles that stop in the third detector. The ratio of the thin to thick detector is smaller than 1:10. Due to the limited telemetry, only the energy loss in the last three detectors was transmitted. Thus, for particles stopping deeper in the instrument, the corresponding ratios are 1:3 and 1:1 for particles that stop in detectors four and five, respectively. In what follows we concentrate on the measurements for ions that stop in the third detector.

Using in-flight measurements it has become common to display the quantity $\Delta E \cdot E_0$ versus $E_0/\Delta E$. The total measured energy and the energy loss in the first detector increase with the charge number and mass. The right panel of Fig. 2 displays the quantity $\Delta E \cdot E_0$ versus $E_0/\Delta E$ using the energy loss $\Delta E$ in the first detector D1 and the total measured energy $E$ from detector D1 to detector D3. Indeed the traces of the different elements are visible ranging from hydrogen to the CNO group and above. The entries below the curves are mainly caused by the fact that the charge collection of the first detector is non uniform from a certain radius outward - decreasing with increasing radius.

In order to investigate this effect in more detail, the right hand panel of Fig 3 shows the measured $\Delta E \cdot E_0$-distribution close to the proton peak. The residuals to the left of the proton peak result from the so called "edge effect". Particles penetrating the detectors beyond their active region produce fewer charge carrier pairs because the electrical field does not drop immediately to zero. To confirm this, a GEANT4 (version 10.0) simulation utilizing the Bertini Cascade and the Quark Gluon string model was set up. The edge effect was modelled by multiplying a radius dependent efficiency to the signal. The corresponding results are displayed in the left panel of Fig. 3. From that figure it is evident that the model is capable to describe the edge effect in the first detector. Electronic effects like the amplification switch between high-gain and low-gain, responsible for the particle population between protons and helium, as well as noise were ignored in the simulation.

The chemical composition of galactic cosmic rays shows that a high signal to noise ratio is needed to determine the chemical composition for the CNO-group. Investigations from in-flight measurements of the second detector show an "edge effect" with a significant smaller impact than that of the first detector. Fig. 4 displays in the upper panel on the left and on the right the measured and corrected $\Delta E \cdot E$ versus $E/\Delta E$ distribution utilizing the energy loss $\Delta E$ in the second detector. Corrections include excluding rear electrons and rear particles by comparing energy deposits in the first two detectors as well as temperature corrections. In contrast to Fig. 2 we find a deviation from a straight line at low values of $E/\Delta E$. This is due

![Figure 3](image-url)
to the fact that the energy loss is comparable to the total energy. However, that effect may be corrected by fitting a second order polynomial to the proton track. Multiplying the data by the corresponding inverse function leads to lines that are parallel to the $\Delta E$-axis. The lower row in Fig. 4 compares the simulation using an adapted model for the edge effects in the second detector and a flat energy spectrum with the measured and corrected distribution. The simulation was performed with a large number of particles in order to clearly show the tracks of protons, helium, carbon, nitrogen and oxygen. Comparing the simulated and measured corrected distributions we find a good agreement if we take into account that neither energy spectra, abundance, electrons nor like $^3$He have been taken into account.

4. Results
Energy spectra for galactic and if present, anomalous, protons, helium, carbon, nitrogen, and oxygen in the energy range from a few MeV/nucleon to several 100 MeV/nucleon were determined by Christian 1989, [10]. Fig. 5 displays 12 hour averaged count rates of $\sim13$ to $\sim27$ MeV/nucleon protons (black curve) and ions (red curve) from Helios 1 and Helios 2 from launch to September 1977, respectively. For our analysis only data with a proton count rate below 0.002 counts/second was used. The lower panel of Fig. 6 shows the simulated $\Delta E \cdot E$ distribution for helium and above. From that figure we find peaks that correspond to boron, carbon, nitrogen, oxygen, and neon. In order to determine the abundances, each peak was fitted with a corresponding Gaussian function. The corresponding lower panel shows the fit residuals which demonstrate the goodness of the fit. We find a typical width $\sigma$ of 0.03 that allows us to separate between C, N, O, and Ne by more than $3\sigma$. Note the small impact of the edge effect on the data between the fits compared to the strong edge effect on protons in detector A (Fig. 3). The
Figure 5. The upper and lower panel display the 12 hour averaged count rates of \( \sim 13 \) to \( \sim 27 \) MeV/nucleon protons (black curve) and ions (red curve) from Helios 1 and Helios 2 from launch to September 1977, respectively. For details see text.

| Element   | Position | \( \sigma \) | Total number | relative abundance (Si) |
|-----------|----------|--------------|--------------|-------------------------|
| helium    | 3.27     | 0.03         | 11849        | 95500                   |
| boron     | 4.52     | 0.03         | 71           | 570                     |
| carbon    | 4.73     | 0.03         | 348          | 2790                    |
| nitrogen  | 4.94     | 0.03         | 102          | 820                     |
| oxygen    | 5.11     | 0.03         | 460          | 3700                    |
| neon      | 5.42     | 0.03         | 89           | 720                     |
| magnesium | 5.66     | 0.03         | 119          | 960                     |
| silicon   | 5.86     | 0.03         | 124          | 1000                    |

Table 2. Results of the fit using a Gaussian to the data in Fig.6. The position and \( \sigma \) give the position of the maximum and the width of the Gaussian in \( \log(E_B \cdot E_{total}/MeV^2) \). The total number is calculated by integration of the Gaussian function. The relative abundance is given with respect to silicon.

The same was done with the measured data, leading to the results summarized in Tab. 2. In order to estimate the elemental separation of the instrument the figure displays the Gaussian fits for B, C, N, O, Ne, Mg, and Si. From this the background distribution can be analyzed further and the edge effect and possible further nuclei like \(^3\)He can be investigated in more detail. The total number of counts varies between 70 for boron and 12000 for helium. Since abundances are given relative to silicon, the statistical accuracy cannot be better than 10% for helium and increases to more than 15% for boron. However, the relative abundances differ significantly from the ones given in Tab. 1. This can be explained mainly by the fact that in contrast to the work by [George et al. 2] the values are not normalized to a reference energy. While the channel analyzed here covers an energy range from 13 to 27 MeV/nucleon for helium, it measures heavier elements at much higher energies. Thus an extended analysis is needed that includes other energy channels from the Helios instrument in order to define a single energy range that is covered by all species.
Figure 6. The blue curves show the left projection (1-dimensional representation) of the different measured elements and simulated distribution. The other colored curves are the result of fits by a Gaussian to the data. The bottom panels display the residuals of the fit, indicating the goodness of the fit. Note that the y-axis are on logarithmic and linear scale on the top and bottom, respectively.
5. Summary and future work
Here we analyzed in detail a channel that counts particles in the energy range from \(\sim 13\) MeV/nucleon to \(\sim 27\) MeV/nucleon for protons and helium. Using a modified \(dE/dx - E\) method we could show that the instrument is capable of separating all major chemical elements from hydrogen to silicon. In order to determine their chemical composition a detailed instrument simulation for different particle species has been performed utilizing a newly developed model of the E6 instrument. This model includes the edge effect. Using a total quiet time span of four years measurements the instrument counted more than 10000 helium, about 350 carbon and 460 oxygen nuclei. This allows to investigate radial structures within the inner heliosphere. In order to determine the chemical composition at single energy intervals, other coincidence channels need to be evaluated and the corresponding response function calculated. The result of this analysis will allow us to investigate the chemical composition during the solar minimum from 1974 to 1977.

Acknowledgements
We acknowledge the use of the SEPServer data base: The SEPServer project has received funding from the European Community’s Seventh Framework Programme (FP7/2007-2013) under grant agreement nr 262773.

Further we acknowledge the International Space Science Institute (ISSI) and the ISSI Team "Exploration of the inner Heliosphere what we have learned from Helios and what we want to study with Solar Orbiter".

References
[1] Engelmann J J, Ferrando P, Soutoul A, Goret P and Juliusson E 1990 Astronomy and Astrophysics 233 96–111
[2] George J S, Lave K A, Wiedenbeck M E, Binns W R, Cummings A C, Davis A J, de Nolfo G A, Hink P L, Israel M H, Leske R A, Mewaldt R A, Scott L M, Stone E C, von Rosenvinge T T and Yanasak N E 2009 Astrophysical Journal 698 1666–1681
[3] Ferrando P, Lal N, McDonald F B and Webber W R 1991 Astronomy and Astrophysics 247 163–172
[4] Duvernois M A and Thayer M R 1996 Astrophysical Journal 465 982
[5] McDonald F B and Ludwig G H 1964 Physical Review Letters 13 783–785
[6] Heber B, Kopp A, Fichtner H and Ferreira S E S 2005 Advances in Space Research 35 605–610
[7] Kunow H, Wibberenz G, Green G, Müller-Mellin R and Kallenrode M B 1991 Physics of the Inner Heliosphere II. Series: Physics and Chemistry in Space 21 243–342
[8] Agostinelli S e 2003 Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 250–303
[9] Lave K A, Wiedenbeck M E, Binns W R, Christian E R, Cummings A C, Davis A J, de Nolfo G A, Israel M H, Leske R A, Mewaldt R A, Stone E C and von Rosenvinge T T 2013 Astrophysical Journal 770 117
[10] Christian E R 1989 Evidence for anomalous cosmic ray hydrogen Ph.D. thesis California Institute of Technology, Pasadena.