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A high energy telescope for the Solar Orbiter

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Abstract

A concept for a highly integrated High Energy Telescope with neutron detection capabilities (HETn) is under development. In the current design for implementation on a spinning platform, the instrument consists of one solid-state detector telescope with coincidence electronics. The instrument further includes a CsI scintillator that is read out by photo-diodes. A 30 g plastic scintillator will offer measurement capabilities for low-energy (~2–100 MeV) solar flare neutrons that are only accessible from an inner heliospheric mission. The scintillators are wrapped in active anti-coincidence shielding. With a total weight of <900 g, the instrument will provide measurements of the time profile, kinetic energy and anisotropy of 4–400 MeV/n protons and heavy ions, and 0.3–15 MeV electrons. This paper will introduce the objectives, the measurement concept, and the critical issues to be addressed by laboratory tests and simulations.

Keywords: Solar energetic particles; Galactic cosmic rays; Solar neutrons

1. Introduction

Solar Orbiter is planned as an ambitious mission that delineates links between the solar corona and the heliosphere. It is a single 3-axis-stabilized spacecraft mission of the European Space Agency. Solar Orbiter will make unprecedented observations in heliosynchronous segments at heliocentric distances between 0.22 and 0.88 AU and out of the ecliptic plane to heliographic latitudes of 30–38°. A near-heliosynchronous orbital segment refers to a period of several days near perihelion when the relative angular motion of the Sun and the Solar Orbiter is small. The spacecraft will use a combination of in situ particle (including neutrons) and field measurements, radio sounding, and visible, UV, and EUV imaging. Studies suggest that in situ particle instruments will have the option to reside on a spinning platform. With this instrument complement and a perspective near synchronous with the Sun's rotation, Solar Orbiter will investigate the inner workings of the solar dynamo, track the birth and evolution of solar activity, and make the first out-of-the-ecliptic images of CMEs during their creation and early evolution stages. Solar Orbiter will also make the first images of the Sun's poles. A High Energy Telescope (e.g., Dröge, 2001), suggested here with neutron detection capabilities (HETn), will play a key role within the Solar Orbiter payload. HETn will investigate the acceleration of particles and 3-D heliospheric structure with the observation of energetic

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particles. Solar Orbiter provides the ideal vantage points for HETn, where for the first time particle propagation effects can be separated from temporal and spectral variability of energetic particle sources.

2. Scientific objectives

The unique orbit of Solar Orbiter will allow us to study the importance of different energetic particle populations at different locations in the inner heliosphere. The time-varying complex structure of the Sun's magnetic field results in a continuous heating of the solar corona to several million degrees. Active regions in the corona accumulate and store magnetic energy. Solar flares and coronal mass ejections (CMEs) occur when this stored magnetic energy is suddenly set free. Often these eruptions release solar energetic particles (SEPs) including electrons, protons, and heavy nuclei. As illustrated in Fig. 1, electrons are frequently accelerated to energies of several MeV, ions to above 100 MeV/n. In rare cases electrons were observed up to ~50 MeV, ions up to 1 GeV/n. Energetic particles carry the information about their source and acceleration into regions of the heliosphere that are accessible by spacecraft. Spectral and compositional signatures, however, are affected and altered by particle transport effects on the path along heliospheric magnetic field lines. Variability in elemental, isotopic, and charge state composition observed at 1 AU have indicated that several particle acceleration processes generate solar energetic particles (Mason et al., 1986; Reames, 1993; Möbius et al., 2002; Posner, 2004). With its proximity to particle acceleration processes close to the Sun, the Solar Orbiter will allow measurements of more pristine characteristics of the highly energized SEP populations than ever before. The HETn design is optimized for observations of the high-energy (4–400 MeV/n) elemental composition of solar energetic particles.

In the inner heliosphere, transient solar activity modulates the intensity of anomalous and galactic cosmic rays (ACRs and GCRs). These high-energy particles (<100 MeV/n to ~10 GeV/n for ions) are believed to originate from processes at the termination shock (Jokipii, 1986) and outside the solar system, respectively. The intensity of GCRs depends on the phases of the 11-year solar activity cycle, but also on the 22-year solar magnetic cycle. GCRs probe the large-scale magnetic structure of the heliosphere and provide information about the 3-D structure of the interplanetary magnetic field. The unique aspect of the Solar Orbiter mission is its near Sun-synchronous orbit phase, which allows separating temporal, transient GCR modulation effects from the otherwise dominating influence of solar rotation. With HETn observations, Solar Orbiter ideally complements modulation results obtained from the Ulysses mission (e.g., Heber et al., 2002) that covered a wide latitude range at intermediate distances (1–5 AU) from the Sun.

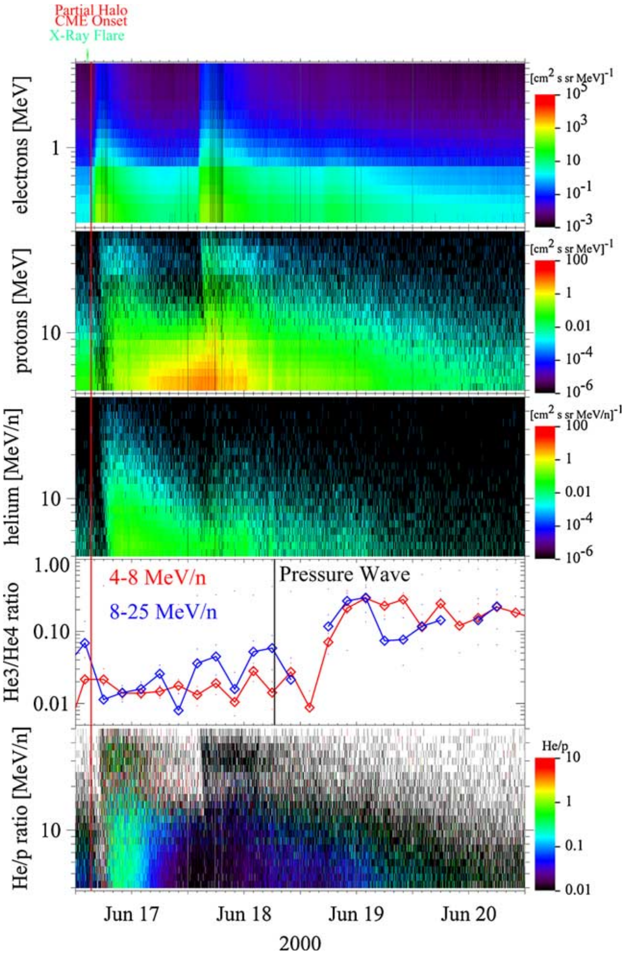

Fig. 1. Spectrograms of electrons, protons and helium during flare and CME activity in June 2000. The bottom panels provide with the ^{3}He/^{4}He ratio and p/He ratio isotopic and composition information for this time period. Observations on the energetic particle composition were made by the COSTEP/EPHIN sensor onboard the SOHO spacecraft at 1 AU distance from the sun.

Other particles in the scope of the HETn investigation are accelerated in compression regions that form in the heliosphere, such as interplanetary, CME-associated shocks and corotating interaction regions. It is expected that Solar Orbiter will intersect CME-associated shocks at the smallest distance from the Sun ever, therefore providing valuable data on the early stage of shock acceleration. Furthermore, the magnetosphere of Jupiter is known as a major source for high-energy electrons (Simpson et al., 1974). Recurrent 'quiet time increases' from Jovian electrons (JEs) were first detected at Earth orbit (McDonald et al., 1972), where the ~13 month periodicity results from seasons of magnetic connectivity between Jupiter and Earth. More recently, Heber et al. (2003) unambiguously identified Jovian electrons at latitudes > 30°. JEs are of unique relevance as a verification tool for solar modulation and heliospheric transport models as of a known, localized source of significant quantities of energetic particles at large distances from the Sun. For instance, a 27-day modulation frequency of Jovian electrons stemming from solar rotation is observed from Earth orbit. At Solar Orbiter, the influence of the recurrent solar modulation period will not interfere with short term variations of JEs, which allows for the first time to study remotely the potential variability of JEs, so far considered as a "standard candle", over extended periods of time.

If the extreme energization of particles in the flare region exceeds nuclear binding energy limits, it is inevitable that a particle zoo is created in high-energy collisions, accompanied by the emission of γ-rays with characteristic nuclear and meson decay lines. In these γ-ray flares, atomic nuclei break up and release neutrons that, due to charge-neutrality, freely escape into space. Neutrons decay after ~15 min therefore only missions to the inner heliosphere open up a window to observe solar flare neutrons in sizable quantities below 100 MeV. Fig. 2 illustrates the presence of solar flare neutrons and quantifies the total number of neutrons that can be detected at various distances with the use of 30 g of scintillation plastic. The calculation is based on a low-energy extrapolation of the emissivity of the large flare on 1982 June 03 (Chupp et al., 1987). Other estimates of low-energy neutron fluxes exist, but these are based on indirect observations of neutron-decay electrons (e.g., Dröge et al., 1996) and protons (e.g., Evenson et al., 1983) at 1 AU.

Scientific objectives of the HETn from the vantage point of Solar Orbiter are:

- To investigate timing, spectra and composition of solar energetic particles, in particular of shock- and flare-accelerated ions at highest energies (4–400 MeV/n), where timing uncertainties are minimal.
- To explore new ground in observing 2–100 MeV solar flare neutron spectra, and simultaneous are-associated anti-matter (positrons).
- To probe heliospheric structure (largely) independent from solar rotation with galactic cosmic ray (100–400 MeV/n) and Jovian electron (250–15 MeV) observations.

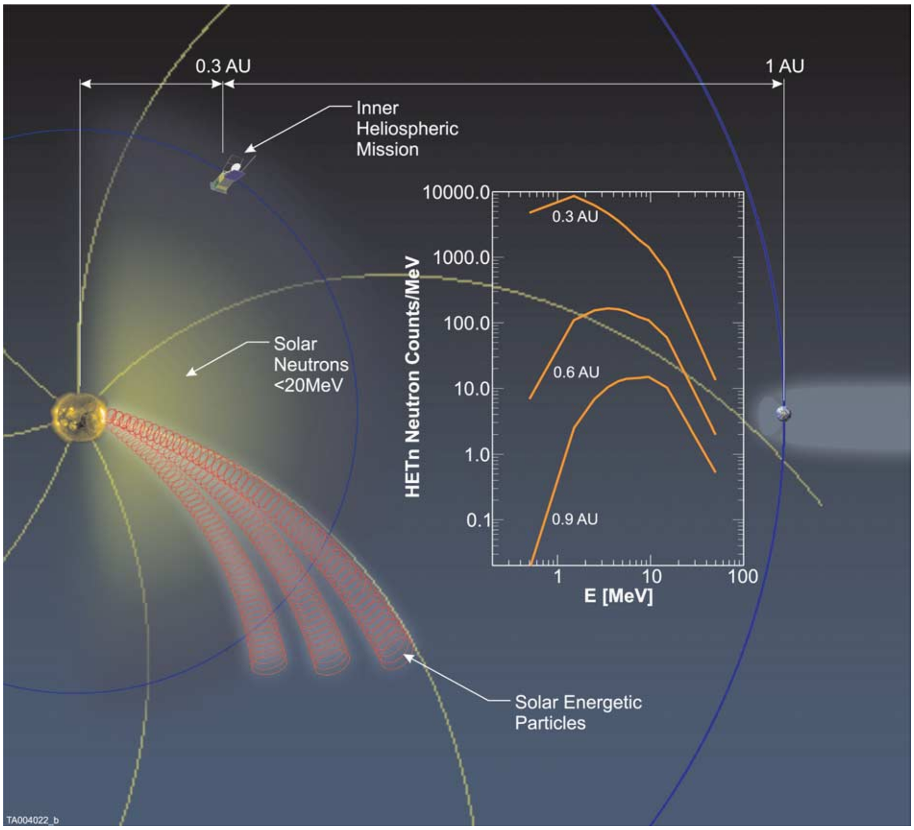

Fig. 2. Schematic view of the Sun and inner heliosphere from above the ecliptic plane. A solar flare is indicated along with the distributions of energetic charged particles (red) and solar neutrons (yellow shading). The neutron distribution of energies less than 20 MeV drops exponentially with increasing distance from the Sun due to the combined effects of spatial expansion ($1/r^2$) and neutron decay. Inner heliospheric spacecraft provide the unique opportunity of measuring neutrons below 100 MeV. A measurements of this type will be the first look in to the unaltered spectrum of massive energetic particles generated in a flare during its initial acceleration phase.

3. Science implementation

The High-Energy Telescope with neutron detection capabilities (HETn) combines a solid-state detector (SSD) stack with a CsI calorimeter in a concise, weight-saving way. The CsI crystal and 30 g of scintillation plastic are fully encapsulated in anti-coincidence material (Fig. 3), therefore providing HETn with the capabilities to detect charge-neutral radiation. The current design requires only a mass of <900 g and 4 W of the limited resources of the Solar Orbiter mission, which includes the sensor head and separate analog and digital electronics boards. Anisotropy information will be provided by the spacecraft assuming that a spinning platform will be implemented (1 SSD telescope version). Alternatively, the HETn can be modified in a weight-saving way that two or three view cones share the CsI calorimeter.

The multiple-coincidence technique used by HETn provides high signal-to-noise ratios and good particle identification capabilities. The highest data products of HETn are time-dependent particle spectrograms that are differentiated by energetic particle species as shown in Fig. 4. Fig. 3 provides sample paths for various types of particles in the detector that are identified as follows:

- *Ions*. Highest priority of HETn is the characterization of the elemental composition of SEPs and low-energy galactic cosmic rays. The geometry of the instrument is chosen in such a way as to guarantee elemental resolution for ions with charge numbers $1 \leqslant Z \leqslant 26$. The calorimeter stops protons with energies <100 MeV, Fe ions up to 270 MeV/n. Due to their relatively large mass, ions scatter electrons in the detector material without significant change in direction. Thus, the path of energetic ions in the HETn is, to a high degree, along a straight line. The acceptance angle of 36.7°, which provides for $0.23\,\text{cm}^2$ sr geometric factor of the instrument, is chosen in order to lead to conformity of path lengths. The shape of the CsI(Tl) scintillator is adapted to the field of view in order to minimize the weight of the instrument. We perform identification of ion species with the dE/dx vs. E method (McDonald and Ludwig, 1964). Here, the ion kinetic energy deposited per unit length multiplied by the total energy is, according to the Bethe–Bloch relation, proportional to Z^2A (Z, nuclear charge number; A, nuclear mass number of element). The low-energy threshold for ions is determined by the choice of detector A. Minimally ionizing particles that penetrate the chain of detectors $ABCD$ and leave the system through G, and vice versa, will be accepted and counted in a separate channel. Here, the uniformity of path lengths that is guaranteed by the shape of detector D is critical for particle identification beyond ~100 MeV/n. This channel extends the energy range of the instrument to accommodate up to ~500 MeV/n ion spectra with elemental resolution based on multiple dE/dx analysis.

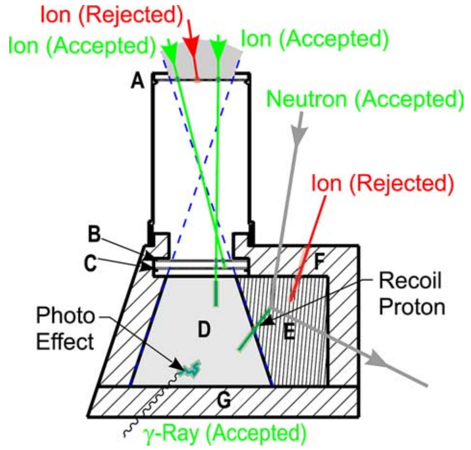

Fig. 3. Sketch of the HETn sensor with sample paths of energetic ions, neutrons, and γ-rays in the detector. Footprint dimensions are ~11 by 11 cm with a height of ~12 cm. The SSDs A–C define the aperture for charged particles. The scintillators D and E are surrounded by anti-coincidence elements (F, G) and provide stopping power for charged particles as well as detection capabilities for neutral (neutrons and γ-rays) ionizing radiation. The particle paths indicate where energy losses occur (wider path). Charge-neutral particles are colored grey. Accepted (rejected) particle paths, including secondaries, are marked green indicating allowed (rejected) coincidence types.

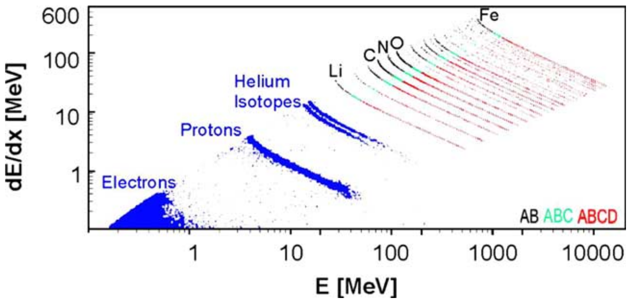

Fig. 4. Simulation of the heavy-ion energy loss matrix for HETn. The simulation is superposed on SOHO/COSTEP-EPHIN measurements for electrons, protons and helium isotopes. This simulation uses modeled GCR spectra together with instrument properties and the intended data compression scheme. The crucial capability of HETn resolving energy spectra for individual ion species up to $Z = 26$ will be tested in laboratory calibrations.

- *Neutrons*. Previously unexplored <100 MeV solar flare neutrons with life times of ~15 min populate only the inner heliosphere in measurable quantities. Knowledge of the spectrum and temporal variability of solar-flare neutrons constrains models on solar-flare initiation and flare-associated particle acceleration. The use of a scintillator anti-coincidence shield F and G in Fig. 3 is a requirement for neutron detection. Since neutral particles do not interact with electrons, which are the source for light emission in scintillator materials, the detection requires other means of energy transfer. In our scintillator system *DE*, neutrons of 2–100 MeV are detected indirectly by elastic scattering with protons, this way transferring kinetic energy to hydrogen nuclei in the plastic detector *E*. Plastic detectors with their high hydrogen content are an ideal material for neutron detection. Recoil protons carry on average half the kinetic energy of the incoming neutron. The detector has a 4-π field of view. High energy neutrons have a higher likelihood of detection as *DE* coincidences if the source is located on the side the plastic detector is facing.

- *γ-rays*. γ-rays are the by-product of high-energy nuclear interactions. γ-ray lines are usually observed in the strongest flares. Direct observations of γ-rays from flares are not possible from the Earth if the flare is located behind the limb. γ-rays can also penetrate the anti-coincidence shield undetected and provide signals in *D* and *E* via the photoelectric effect, Compton scattering and pair production. The high-Z CsI material of *D* has a vastly higher sensitivity for the detection of γ-rays than the plastic of detector *E*. *D* signals will be used as a γ-ray spectrometer between the detector noise level of several hundreds of keV up to the physical limit of the CsI material of ~2 MeV.
- *Electrons and positrons*. Solar flares accelerate electrons to energies of several MeV. Observations of relativistic flare electrons are vital for event onset timing studies. Electrons are low linear-energy-transfer (LET) particles with on average large ranges in detection materials. HETn will measure electrons in the range from 150 keV up to 15 MeV, which also covers most of the Jovian electron spectrum. The distinction from ions will be performed with d*E*/d*x* vs. *E* analysis. It will be necessary for quantitative assessment of energy spectra to derive detailed response functions from calibration data and from Monte Carlo simulations. A distinct coincidence condition will be applied for the detection of positrons, which are by-products of flare processes in the corona. The annihilation of the positron with a detector *B* electron generates characteristic 511 keV X-rays. *AB*-coincidences with electron-type energy loss signals in coincidence with a light pulse in *D* equivalent to the characteristic X-ray energy deposit define the positron channel.

The wide dynamic range of HETn allows observations of electrons and ions with $1 < Z < 26$. Fig. 4 shows the HETn d*E*/d*x* vs. *E* energy loss matrix for particles that stop within the detector. The simulation of ion energy losses is based on geometry and data compression scheme of HETn, by taking into account the elemental composition and spectrum of GCR ions. The simulation is combined with SOHO/COSTEP observations of electrons, protons, and helium from solar energetic particles observed in October, 2000.

4. Calibration

A technical cooperation agreement is in place between Southwest Research Institute (San Antonio, TX, USA) and the University of Kiel (Germany) in order to further develop and test the HETn instrument for the Solar Orbiter mission. HETn uses only low-risk, flight-proven technologies that are based on SOHO/COSTEP (Müller-Mellin et al., 1995) and ISS/Matroshka heritage. Calibration of the HETn laboratory model is currently underway and will include exposure to high-energy ions, neutrons, electrons and positrons. Specific tasks to be specified are the elemental resolution for ions, and the energy-dependent response functions for electrons, positrons and neutrons.

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