Direct Mass Spectrometric Measurement of Interstellar Neutral Gas

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Abstract. For the direct measurement of neutral gas in the heliosphere, e.g. interstellar neutral gas, a sensitive neutral particle imaging detector is needed in the energy range of 10 eV–1000 eV. For successful detection, the neutral particles have to be ionized first, which will be accomplished via surface ionization. This method is currently successfully employed by the LENA instrument on the IMAGE mission. We present a laboratory prototype of an improved version for a neutral particle mass spectrometer and will discuss its instrument characteristics. Performance is evaluated with emphasis on the neutral to negative ions conversion for H and O and the collection of these ions by the mass spectrometer. Measurements of the detection efficiency of the prototype for primary neutral hydrogen and oxygen atoms are presented. Several conversion surfaces were investigated and all are potential candidates for a neutral particle imaging instrument of the next generation.

Introduction

Measurements of the properties of the local interstellar medium LISM (temperature, density, composition) will give information about the evolution of the solar system and our galaxy. The sun with its solar wind creates a cavity in the plasma of the LISM, the heliosphere, and charged particles are efficiently deflected by this obstacle. The neutral fraction of the LISM, however, is not bound toelectro-magnetic fields and therefore can deeply penetrate into the solar system. As the Sun moves with a velocity of approximatively 26 km/s relative to the LISM a directed inflow of interstellar neutrals is observed. This neutral particle flux is affected by gravitational effects, photo ionization and charge exchange processes. At a distance of a few astronomical units from the Sun these effects become small enough to make it possible to infer the properties of the LISM by measuring the local properties of the inflowing neutrals. This has been done for helium by the GAS instrument on the ULYSSES spacecraft [*Witte et al.*, 1992].

We have built and tested a prototype instrument for the detection of neutral hydrogen, carbon and oxygen atoms in a velocity range of 10 km/s to 100 km/s corresponding to an energy range of 10 eV–1000 eV depending on species. This velocity range is what has to be expected when observing the inflow from an spacecraft in a solar orbit or on an escape trajectory from the solar system. Our prototype allows angular resolved direct measurement of the interstellar gas flow intended for future missions, such as NASA's Interstellar Pathfinder, Outer Heliospheric Imager, or Interstellar Probe.

Experimental

Neutral particle sources from two independent facilities were used for our investigations. In the CASYMS chamber [*Ghielmetti et al.*, 1983] at the University of Bern a neutral atom beam was produced by scattering a low energy positive ion beam from a tungsten surface. In the source at the University of Denver neutrals were produced by photo-detaching electrons from negatively charged primary ions [*van Zyl et al.*, 1996].

Figure 1 shows a schematic drawing of the NICE (Neutral Interstellar gas Composition Experiment) prototype. Neutral particles enter the instrument through a charged particle deflection system (not shown; this was part of the neutral source for our tests) and an aperture. For successful detection the incident neutrals must be ionized first which is accomplished by surface ionization. Surface ionization is currently successfully employed by the LENA instrument on the IMAGE mission [*Moore et al.*, 2000]. Several different conversion surface materials were tested: A hydrogen passivated CVD diamond surface [*Wurz et al.*, 1997], a polished MgO bulk crystal [*Wieser et al.*, 2002], a layered sample with a $BaZrO_3$ top layer [*Jans et al.*, 2001], and tungsten LENA flight spare surface [*Moore et al.*, 2000]. The investigated conversion surfaces were all polished to a roughness of a few nm RMS. An extraction lens postaccelerates negatively ionized particles from the conversion surface to an energy of 15 keV before they are analyzed in a time-of-flight mass spectrometer (TOF). The lens focuses particles to different positions at the exit of the lens depending on the particle energies at the conversion surface resulting in a coarse primary energy resolution. Angular resolution of the incident neutrals is provided in a direction out of the plane in Figure 1 (1-dimensional pinhole camera configuration). The extraction lens was inherited from the LENA instrument. For the current tests we did not measure the angular resolution as it would be determined by the number of pixels of the TOF used. The TOF used in the prototype was an adapted CODIF [*Rème et al.*, 1993] instrument.
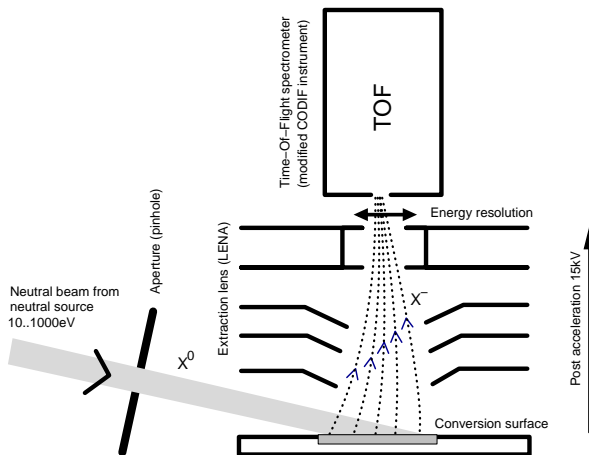

Figure 1. Schematic view of the NICE prototype.

The lens subassembly was mounted on a linear table to allow for the scanning of the TOF entry slit over the lens exit plane to get coarse primary energy information. In a flight instrument the linear table would be omitted and the scanning would be performed by using a TOF with position resolving entry system. The NICE instrument was mounted on a turntable to change the angle of incidence of the primary beam onto conversion surface.

The following properties were measured to characterize the prototype: depen-

dence of the efficiency of the conversion surface from different angles of incidence of the primary neutrals, sputtering at the conversion surface, energy resolution of the extraction lens, and overall detection efficiency of the instrument. The detection efficiency η_{total} of the instrument is a product of the efficiencies of the different subsystems and can be expressed as

$$\eta_{total} = \frac{N_{measured}}{N_{incident}} = \eta_{ionization} \cdot \eta_{lens} \cdot \eta_{C-foil} \cdot \eta_{TOF}$$

where $N_{measured}$ represents the number of valid TOF counts per second, $N_{incident}$ the number of particles that hit the conversion surface per second, $\eta_{ionization}$ the fraction of particles that get negatively ionized upon reflection at the conversion surface, η_{lens} the collection efficiency of the extraction lens, η_{C-foil} the transmission of the C-foils in the TOF, and η_{TOF} the detection efficiency of the TOF depending on species. $\eta_{ionization}$ shows a dependence on primary particle energy and species [*Wurz et al.*, 1997; *Jans et al.*, 2001; *Wieser et al.*, 2002]. η_{C-foil} and η_{TOF} depend on species and postacceleration voltage; the values used were taken from [*Kistler*, 2000].

Results

Angular sensitivity   The scattering properties of a conversion surface depends strongly on the angle of incidence of the primary particles [*Wieser et al.*, 2002]. In the Denver chamber we varied the angle between the incident neutral beam and the surface normal between 76° and 84°. No significant angular dependence of the instrument detection efficiency could be observed. The observed variations in the count rate when changing the angle were all due to the relatively small size of the conversion surface used (25 mm diameter) and small beam misalignments of the order of a fraction of a millimeter.
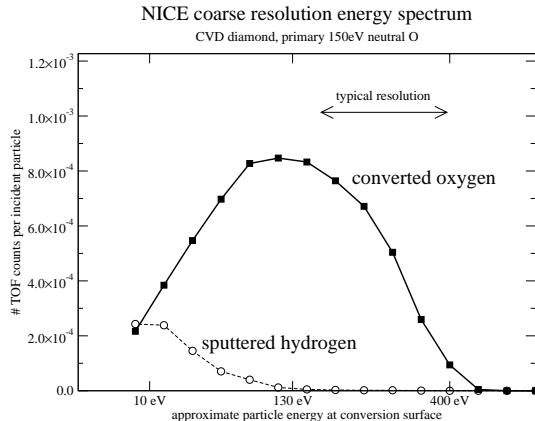

Figure 2. Scan over the exit of the extraction lens

Energy resolution and sputtering   Figure 2 depicts an energy spectrum with the TOF entry slit scanned over the exit of the extraction lens when using a 150 eV primary oxygen beam and the CVD diamond conversion surface. After subtracting the background, fit functions were applied to the measured TOF spectra to separate the observed species at each position at the exit of the lens. The approximate energy scale on the plot was obtained by using different primary energies and by observing the position of the maximum of the oxygen peak. This maximum represents 85 % of the primary energy, as 15 % is the approximative energy loss when reflecting a particle from the conversion surface. The peak is rather broad because the extraction lens

has only a limited focusing capability. Nevertheless sputtered particles from the conversion surface can clearly be separated from converted incident neutrals. The energy distribution of the sputtered particles - mostly hydrogen - peaks at a few eV and these particles appear thus at the low energy side of the lens.
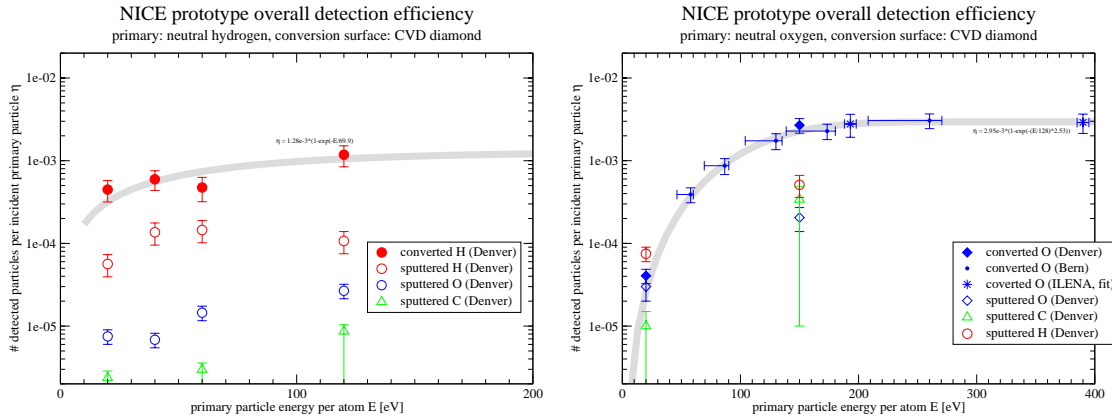

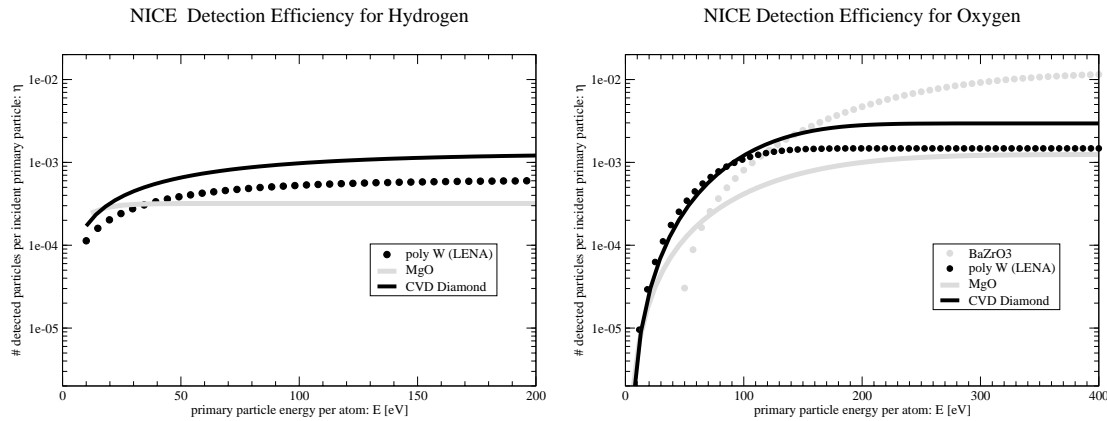**Figure 3.** Detection efficiency for neutral H and O with the CVD diamond conversion surface

Figure 4. Detection efficiency neutral H and O for different conversion surfaces

Detection efficiency Using the known scattering and ionization properties of the conversion surfaces the collection efficiency of the lens η_{lens} was found to be 0.11 to 0.13 independent of the energy of the primary particles. The main energy dependence of the detection efficiency is thus due to the energy dependence of the ionization efficiency. After subtracting the sputtered fraction the overall detection efficiency is calculated by integrating over the energy distribution at the exit of the lens. Figure 3 depicts the detection efficiency of the prototype for primary neutral oxygen and the CVD diamond surface depending on primary energy. The results obtained using the two different neutral sources, in Bern and in Denver, agree very well. Figure 4 depicts a comparison of the instrument performance depending on primary energy, type of conversion surface, and primary species. In these summary plots only the empirical fits shown as gray line in Figure 3 are used. For primary oxygen a strong energy dependence over several orders of magnitudes was observed whereas for primary hydrogen the detection efficiency curves are almost flat.

Discussion

Angular sensitivity   No dependence of the detection efficiency from the angle of incidence was found. This is compatible with earlier measurements [*Wieser et al.*, 2002] that showed no dependence of the ionization efficiency of a conversion surface from the angle of incidence as long the angle larger than $80°$, i.e. flat. Although the width of the scattering distribution increases at steeper angles and also at higher particle energies, the extraction lens can focus this.

Energy resolution and sputtering   The energy resolution of the extraction lens allows to separate sputtered particles from converted incident neutrals. The energy distribution of the sputtered particles peaks at a few eV, thus all sputtered particles appear at the low energy side of the exit of the extraction lens. Sputtered particles consist mainly of hydrogen. The main sources for sputtered particles will be helium and oxygen as they are the most abundant elements next to hydrogen. Sputtering due to primary hydrogen is not probable due to the low energy of the neutral hydrogen atoms (70km/s $\approx$25 eV). Assuming a CVD diamond conversion surface and using elemental abundances of the neutral inflow taken from [*Geiss and Witte*, 1996], hydrogen sputtered by incident 70km/s oxygen atoms amounts for about 1 ‰ of the total hydrogen counts and about 4 % of the hydrogen counts will be due to sputtering from helium. Effects that modify the elemental abundances, i.e., at the heliospheric interface, are neglected in this estimation.

In our experiment we put the conversion surface from air into vacuum and started measurements after approximately one day then the pressure was below 10^{-6} mbar. Even within the few hours of measurement we observed a systematic decrease in the sputter rate, indicating cleaning of the surface with time. The observed sputter rates are thus an upper limit. On a mission heading out to the heliopause the instrument would have several years time available to out-gas. The NICE prototype could also be combined with a GAS type instrument sensitive for helium to constrain the sputter rate and also to extend the elemental range to helium.

Detection efficiency   Assuming a neutral density for hydrogen of $0.1\,\text{cm}^{-3}$ and an apparent inflow velocity of $70\,\text{km/s}$ and integrating over the whole angular distribution approximately count rates of $75\,\text{counts/s}$ for hydrogen and $0.35\,\text{counts/s}$ for oxygen are expected. The observed detection efficiencies are large enough to get useful statistics within hours. This values can be obtained with the current prototype. Without significant changes in the design the count rate can be increased by a factor of 4 by using a larger conversion surface, by another factor of 2 by optimizing the extraction lens and the interface extraction lens - TOF, and by a factor of 1.5 by optimizing the TOF. Including this improvements count rates of $900\,\text{counts/s}$ for hydrogen and $4.2\,\text{counts/s}$ for oxygen can be obtained. Further optimizations are possible by switching from a 1D-pinhole camera sensor to a single pixel telescope as used by the GAS instrument. This would allow to increase the collection efficiency of the lens close to 100 % resulting in another increase of the detection efficiency by a factor of 3 to 4 compared to the optimized 1D-pinhole camera sensor. This way count rates up to $3600\,\text{counts/s}$ for hydrogen and $17\,\text{counts/s}$ for oxygen are possible. The latter is offset by the need of a scanning platform to measure the angular distribution.

Conclusion

We have successfully tested an instrument for the direct measurement of the interstellar neutral gas. The results from the two independent facilities agree very well. The detection efficiency of the instrument is high enough to get reasonable counting

statistics within hours. Sputtered and converted primary neutrals can be separated by their energy distribution at the conversion surface. The detection efficiency of the prototype can be increased up to a factor of 3 for the design used or a factor up to 12 when changing to a single pixel telescope.

Acknowledgements

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