A mass analysis technique using coincidence measurements from the Interstellar Boundary Explorer-Hi (~0.3–~6 keV) detector

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NASA's Interstellar Boundary Explorer (IBEX) mission, scheduled to launch in October 2008, will make the first observations of charge exchange energetic neutral atoms (ENAs) produced near the edge of the heliosphere. IBEX will measure these ENAs with two ultra-high sensitivity, single-pixel ENA sensors in the energy range of ~0.01–~2 keV (IBEX-Lo) and ~0.3–~6 keV (IBEX-Hi), respectively. The primary purpose of IBEX is to measure hydrogen ENAs from the outer heliosphere, but it will also be sensitive to heavier species of ENAs produced anywhere throughout the solar system. For this study, we measured the coincidence response of the IBEX-Hi detector section to H, He, N, and O ions. Based on these results, we have developed an innovative technique in estimating the hydrogen to heavy ion ratio in the signal. This new technique can be applied more widely than the IBEX-Hi detector section, and the basic principle may be useful for other, future space and ground-based measurements. © *2008 American Institute of Physics.*
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NASA's Interstellar Boundary Explorer (IBEX) mission[1] is scheduled to launch in October 2008. IBEX's primary purpose is to make the first observations of energetic neutral atoms (ENAs) produced near the edge of the heliosphere, the region of space dominated by the Sun and its supersonically expanding solar wind. From the all-sky images and measured ENA energy spectra, IBEX will allow us to understand the global interaction of the heliosphere with the local interstellar medium for the first time. IBEX will measure these ENAs with two ultra-high sensitivity single-pixel ENA sensors mounted on opposite sides of a Sun-pointing spinning spacecraft. These sensors, IBEX-Lo and IBEX-Hi, measure ENAs in the energy range of ~0.01–~2 keV and ~0.3–~6 keV, respectively.

While the primary purpose of IBEX is to measure hydrogen ENAs from the outer heliosphere, it will be sensitive to both hydrogen and heavier species of ENAs produced elsewhere in the solar system. The largest source of these nonheliospheric ENAs will be the Earth's magnetosphere, which is a copious producer of ENAs from charge exchange between magnetospheric ions and cold neutral hydrogen atoms in the Earth's geocorona.[2,3] Observations of the Earth's magnetosphere using instruments from the Imager for Magnetophere-to-Aurora Global Exploration (IMAGE) spacecraft revealed an enhanced, sometimes dominant, oxygen population during geomagnetic activity.[4] Counts from regions of the sky that include the magnetosphere will have to be segregated and removed from the IBEX heliospheric images. These emissions, however, will provide a valuable additional science data set for remotely studying the magnetosphere itself.[1] Other sources that IBEX will likely see include the magnetospheres of other planets, especially Jupiter, which is a strong emitter of ENAs,[5] and possibly comets.

That these heavy ENA populations may be measured by IBEX has led us to consider whether any mass information can be obtained from a carbon foil based coincidence detector such as IBEX-Hi.

In this paper, we describe a technique which shows how information on particle mass can be obtained from the IBEX-Hi detector section. For this study, we measured the response of the detector section for several different ion species. These measurements and subsequent analysis of the data provide us with a tool to develop a methodology in estimating the hydrogen to heavy ions ratio and also the number of ions incident on the detector section. The measurements presented here were taken with the IBEX-Hi detector section, but the same basic technique can be applied more widely, and the principle may be useful for other future space and ground-based measurements. To the best of our knowledge, this is the first time that such a technique has been reported in the literature.

The detector section of IBEX-Hi consists of three nearly identical cylindrical chambers 56 mm in diameter and 26 mm in length each separated by a carbon foil and equipped with a channel electron multiplier (CEM) as shown in Fig. 1. The ions (in red), apart from being scattered in angle and energy (e.g., Ref. 6 and references therein), also cause secondary electron (SE) emission from both sides of the carbon foils (CF1 and CF2) as they traverse them (e.g., Ref. 7). Similarly, ions cause SE emission when they hit the aluminum walls of the detector section. The SEs (in green) are then attracted toward the CEMs (*A*, *B*, and *C*) by the potential difference between the CEM (funnel at ~ −1700 V) and the detector section at −6000 V, and trigger signals in the CEMs.

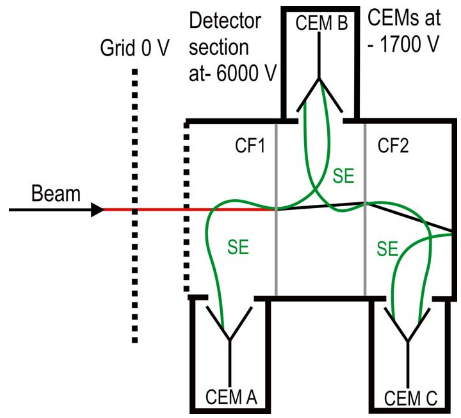

FIG. 1. (Color online) Schematic view of the IBEX-Hi detector as mounted in the vacuum chamber for testing.

When a SE is detected by any of the CEMs a 70 ns coincidence window is started. During this interval, the electronics are triggered to accept and record the events in the other CEMs. At the end of the coincidence window, seven combinations of events are possible: a signal in all three CEMs ($A+B+C$; hereafter called triple coincidence), in two CEMs ($A+B$, $A+C$, or $B+C$, double coincidence), or in one CEM (A, B, or C, single event). There are a number of reasons why an ion does not always generate a triple coincidence. First, the CEM detection efficiency for electrons at ~4 keV is ~70%–80%.[8] Second, not all the SEs generated at the carbon foil reach the CEM and, therefore, escape detection. Third, the SE yield from carbon foils is statistical and, sometimes, the foil produces no electrons.[9] A careful design of the detector section allowed the reduction in single-event noise rates to less than 2 Hz and the coincidence noise rates to much less than 1 Hz.

We measured coincidences generated by H^+, He^+, N^+, and O^+ ions over an energy-per-charge (E/q) range of ~0.7 to 5.4 keV/q. The counts were recorded in 0.5 s samples for typically a few hundred samples for each measurement. The events are exclusive such that a detected ion can only be recorded as one type of event. Thus, a statistical comparison of the number of counts generated for each type of event can provide information on the probability that an ion will be recorded as a particular type of coincidence. We quantify these probabilities using a coincidence ratio defined as the number of counts generated for a specific type of coincidence divided by the total number of counts from all measured events. For example, we define the triple coincidence ratio as

$$ABC = \frac{N_{ABC}}{N_{ABC}+N_{AB}+N_{BC}+N_{AC}+N_A+N_B+N_C} = \frac{N_{ABC}}{N_{\mathrm{Tot}}}, \quad (1)$$

where N_{ABC} is the number of triple coincidence counts, N_{AB}, N_{BC}, and N_{AC} are the number of double coincidence counts, and N_A, N_B, and N_C are the number of single event counts. N_{Tot} is the total count from all coincidence and single events. To calculate the uncertainty σ_{ABC}, in the ABC coincidence ratio, we use the standard deviation of the ABC ratios calculated for each 0.5 s sample.

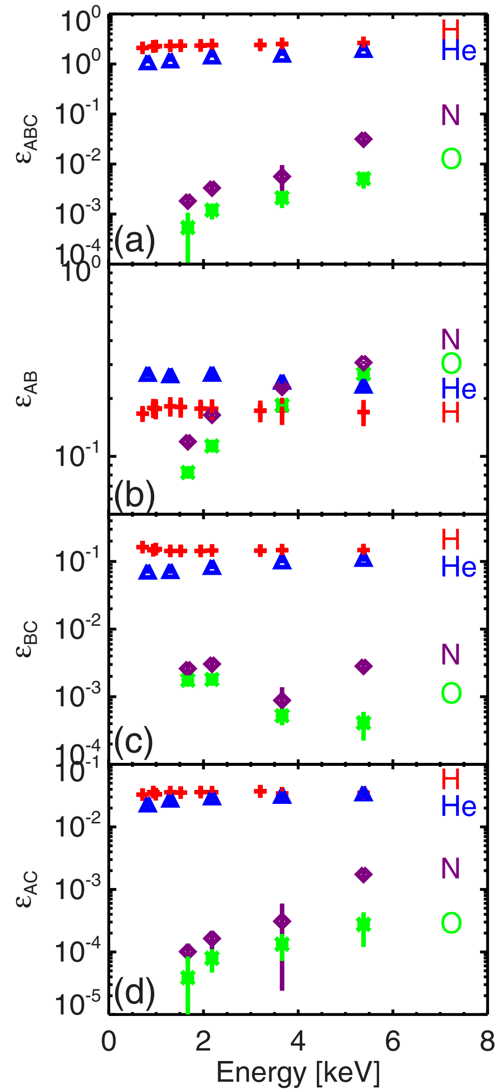

FIG. 2. (Color online) Detection efficiencies of H, He, N, and O for the (a) ABC, (b) AB, (c) BC, and (d) AC coincidence types.

$$\sigma_{ABC} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(ABC - ABC_i)^2}, \quad (2)$$

where n is the number of samples, ABC is the triple coincidence ratio calculated from Eq. (1), and ABC_i is the triple coincidence ratio calculated for the i^{th} 0.5 s sample. Similar equations are used to define the double coincidence (AB, BC, AC) and the single event (A,B,C) ratios. The detection efficiency for a triple coincidence for hydrogen is defined as

$$\varepsilon_{ABC,H} = \frac{N_{ABC,H}}{N_{0,H}} \quad (3)$$

where $N_{ABC,H}$ is the number of triple coincidences and $N_{0,H}$ is the total number of incident H on CF1 derived using the method as described in Ref. 10. Similar equations apply to the other coincidence types and species. We derived the detection efficiencies of H, He, N, and O and show them as a function of energy in Fig. 2 for the (a) ABC, (b) AB, (c) BC, and (d) AC coincidence types. The sum of all efficiencies $(\varepsilon_A+\varepsilon_B+\varepsilon_C+\varepsilon_{AB}+\varepsilon_{BC}+\varepsilon_{AC}+\varepsilon_{ABC})$ is the detection efficiency of an ion and ranges from 0.882 to 0.904 for H, 0.880 to 0.910 for He, 0.637 to 0.833 for N, and 0.615 to 0.828 for

O, between ~0.7 and 5.4 keV. We also note that the detection efficiency is a function of energy.

The efficiency for detecting a triple (ABC) coincidence ratio for O (and N) is reduced by a factor of at least ~470 (and ~80) with respect to that for H. Similar differences are also observed for the AC and BC coincidences. These large differences between the coincidence measurements for hydrogen and heavy ions lead to the possibility of identifying the relative fraction in a mixture of these ions. On the basis of these results, we have developed a technique to identify the mixing of ions measured by the IBEX-Hi detector, thus extending the scientific capabilities possible with this upcoming space mission.

The basis of this technique is to compare the coincidence ratios generated from an unknown source with those measured for H and heavy ions in the laboratory. When a mixture of hydrogen and heavy ions is measured, the resulting coincidence ratios differ from the H laboratory measurements. This difference is a direct function of the ratio between the fraction of H and the heavy ions and the detection efficiencies.

Knowing, on the one hand, the number of coincidences N_{ABC}, N_{AB}, N_{BC}, and N_{AC} and single events N_A, N_B, and N_C in a measurement, and, on the other hand, the detection efficiencies for different species for these coincidence types, we can define the following system of linear equations:

$$N_{ABC} = N_X \varepsilon_{ABC,X} + N_Y \varepsilon_{ABC,Y} + N_Z \varepsilon_{ABC,Z} + \dots ,$$

$$N_{AB} = N_X \varepsilon_{AB,X} + N_Y \varepsilon_{AB,Y} + N_Z \varepsilon_{AB,Z} + \dots ,$$

$$N_{AC} = N_X \varepsilon_{AC,X} + N_Y \varepsilon_{AC,Y} + N_Z \varepsilon_{AC,Z} + \dots ,$$

$$N_{BC} = N_X \varepsilon_{BC,X} + N_Y \varepsilon_{BC,Y} + N_Z \varepsilon_{BC,Z} + \dots ,$$

$$N_A = N_X \varepsilon_{A,X} + N_Y \varepsilon_{A,Y} + N_Z \varepsilon_{A,Z} + \dots ,$$

$$N_B = N_X \varepsilon_{B,X} + N_Y \varepsilon_{B,Y} + N_Z \varepsilon_{B,Z} + \dots ,$$

$$N_C = N_X \varepsilon_{C,X} + N_Y \varepsilon_{C,Y} + N_Z \varepsilon_{C,Z} + \dots . \tag{4}$$

The unknowns of the system of equations are N_X, N_Y, and N_Z and refer to number of incident particles for species $X, Y, Z, \dots$, respectively. $\varepsilon_{i,j}$ is the efficiency for an event-type i and species j. The system has seven equations, one for each coincidence type. These equations are easily solved in cases where seven species or fewer are present. In practice, there is a good probability that only two (e.g., H and O in the Earth's magnetosphere) species dominate and the contributions from other species can be neglected. In this case, we can apply a least square method to find the optimized solution for the linear equations, providing us with the number of particles measured for each species.

Due to the statistical nature of this technique, we cannot determine the mass of an atom on an event by event basis. Moreover, this technique works for cases where the difference in the coincidence ratio is larger than the uncertainties. However, when the number of events is sufficiently large, we will be able to clearly measure the fraction of heavy ions relative to hydrogen in the signal.

The measurements presented here show that ions of different masses yield very different coincidence ratios, which lead to the possibility of identifying heavier ion species among H^+. These differences are used to develop an innovative technique to identify a compositional ratio of H and heavier elements in the source signal allowing the calculation of the number of particles incident on the detector for each species. While this technique was developed specifically for the IBEX mission, it has potential for wider use in future space and ground-based measurements.

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