



**IN SITU MEASURING OF THE COMPOSITION
(HYDROGEN, DEUTERIUM, AND OXYGEN ATOMS)
OF INTERSTELLAR GAS**

Report No. 102

Michael A. Gruntman

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SPACE SCIENCES CENTER

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The composition of neutral gas in the Local Interstellar Medium can be studied by direct, *in situ*, measuring of interstellar neutral atoms penetrating into interplanetary space at the vicinity of the Earth's orbit. A novel experimental approach for *in situ* atom detection, which has never been used earlier in space, is proposed. The technique is based on the conversion of neutral atoms to negative ions at specially prepared sensitive surface. Negative ions are subsequently analyzed in a magnetic analyzer and they are detected by essentially noise-free multiple-coincidence time-of-flight unit. It is shown that interstellar hydrogen, deuterium, and oxygen atoms as well as possibly hydrogen molecules can be measured by the proposed technique. Such an experiment, performed at the Earth's orbit, should provide for the first time the abundances of important constituents in interstellar gas at the vicinity of the Sun. A possibility to use the proposed technique for the study of planetary upper atmospheres and exospheres is briefly discussed.

in the line of sight in the case of Lyman lines and by chemical and physical fractionation in the case of deuterated molecules (*Wannier, 1980; Boesgaard and Steigman, 1985*). The detection of deuterium in cosmic rays is irrelevant to the problem because this component is born by the breakup of primary cosmic ray helium nuclei (*Mewaldt, 1988*).

Interstellar gas oxygen atom abundances are of a much interest for the theories of formation and evolution of the stars (*Wannier, 1980*). On the "local" scale, oxygen in the LISM is believed to contribute to the oxygen component of anomalous cosmic rays (*Cummings and Stone, 1990*). Comparison of the oxygen number density in the LISM, as it is derived from anomalous cosmic ray observations, with the number density from independent *in situ* measurements would be of prime importance and would test proposed mechanisms of the formation of anomalous cosmic rays and cosmic ray particle acceleration in general. No direct experimental data on the number density of oxygen in the LISM is available now.

Neutral ISG from the LISM penetrates our solar system and some interstellar atoms reach the Earth's orbit. This phenomenon presents naturally an opportunity to measure directly the interstellar atoms in interplanetary space. The inflow of interstellar hydrogen and helium has been studied both theoretically and experimentally almost exclusively by optical methods (e.g. reviews by *Axford, 1973; Fahr, 1974; Holzer, 1977; Bertaux, 1984*). The only recent exception is the direct interstellar helium detection experiment on the Ulysses mission (*Rosenbauer et al, 1983, 1984*). Also energetic neutral hydrogen atoms born in the heliospheric interface will be observed in future by the instruments aboard the Relikt-2 mission (*Gruntman et al, 1990*). Continuous development during the last decade of ideas as to how neutral atoms could be detected *in situ* in interplanetary space has brought us to the point to try to also perform *in situ* detection of other atoms of interstellar origin - hydrogen, deuterium, and oxygen. The use of a new technique - based on a conversion of interstellar atoms to negative ions, - which has been never used in space experiments, is proposed.

The best possible place to perform such measurements is from a fast moving interplanetary spacecraft, far from planetary magnetosphere/exosphere influence and as far

as possible from the Sun itself. An ideal mission is the proposed Interstellar Probe (*The Interstellar Probe, 1990; Interstellar Probe Workshop, 1990*). However, such "Gigabuck" missions, though being incomparably exciting, are affected severely by budget considerations and it is wise to look also for a less expensive alternative. Essential measurements could be made, for example, from an Earth orbiting spacecraft with a high apogee (100 000 km) orbit. The proposed experiment on such a spacecraft will provide also the opportunity to flight-prove the new experimental approach and the new instrumentation. The latter is an important issue since, as a rule of thumb, the "flight-worthiness" of the instrument is a must as a precursor to a ride on an interplanetary (to say nothing about interstellar) mission. Therefore the problem of direct *in situ* measurement of interstellar atoms will be considered here with emphasis on a high apogee Earth-orbiting spacecraft. Some of the details of possible direct measurement of interstellar hydrogen atoms at the Interstellar Probe mission were discussed earlier by *Gruntman, 1990b*.

At first, the expected fluxes of interstellar atoms are calculated for the observer at the Earth's orbit. The possible experimental approach is then outlined, and, finally, some details of relevant instrumentation are discussed.

2. PENETRATION OF NEUTRAL ATOMS INTO INTERPLANETARY SPACE

Let us first estimate the expected fluxes of interstellar atoms at the Earth's orbit around the Sun since it seems to be the place for the most feasible experiment. Besides atoms of hydrogen, deuterium and oxygen, for consistency the helium atoms are also considered.

For the purpose of this work, several simplifying assumptions are justifiable. Let us assume that an observer moves together with the Earth along its circular orbit (radius $R_0 = 1 \text{ AU}$) around the Sun with velocity $V_E = (G M_S / R_0)^{1/2} = 29.75 \text{ km/s}$, where G is the gravitational constant and M_S is the solar mass. The velocity of interstellar gas relative to the Sun, which is assumed to be at rest, is $V_0 = 20 \text{ km/s}$ and its vector is in the ecliptic plane (fig.1). We will assume that the temperature of the ISG is $T_0 = 0$. The latter assumption will result in large errors while calculating interstellar gas characteristics in the solar wake region. However, it simplifies calculations dramatically and provides a relatively

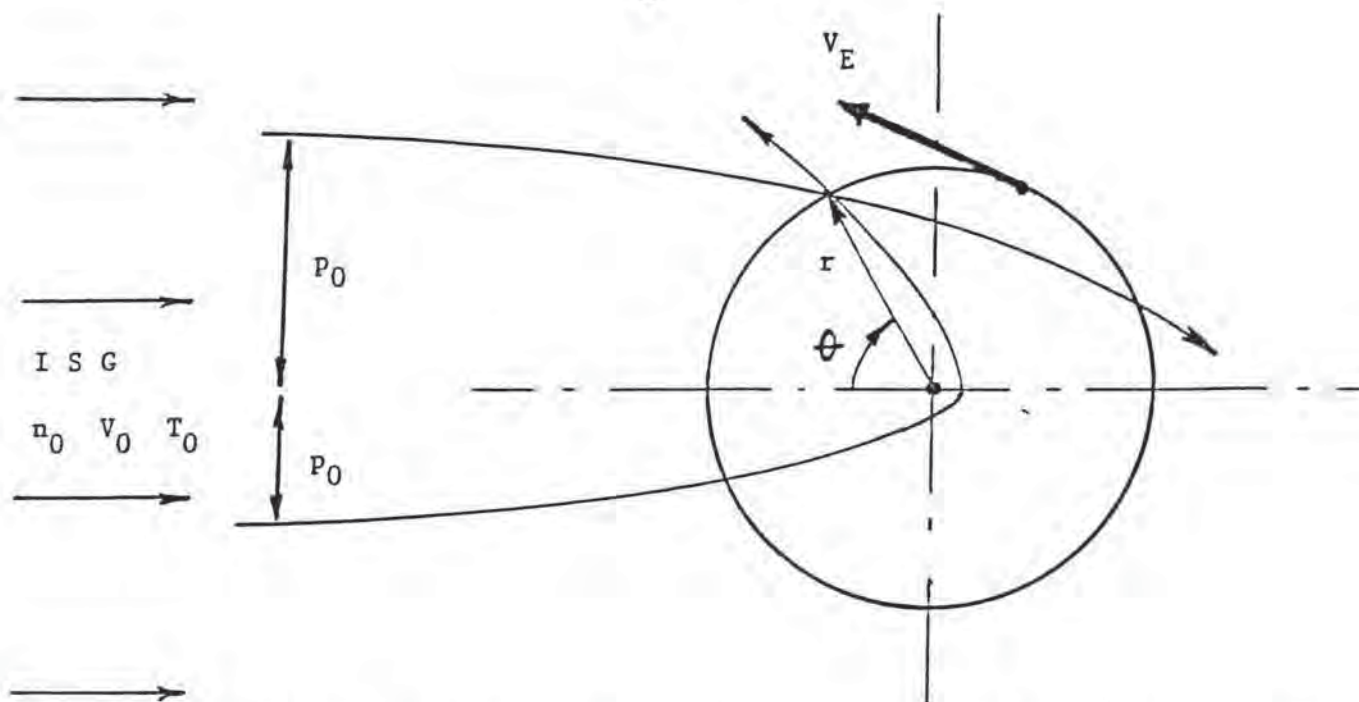


Fig.1. Penetration of interstellar atoms into the Solar system. Two Keplerian trajectories with different impact parameters p_0 lead to each point (r, θ) . V_E is the velocity of the Earth along its orbit around the Sun.

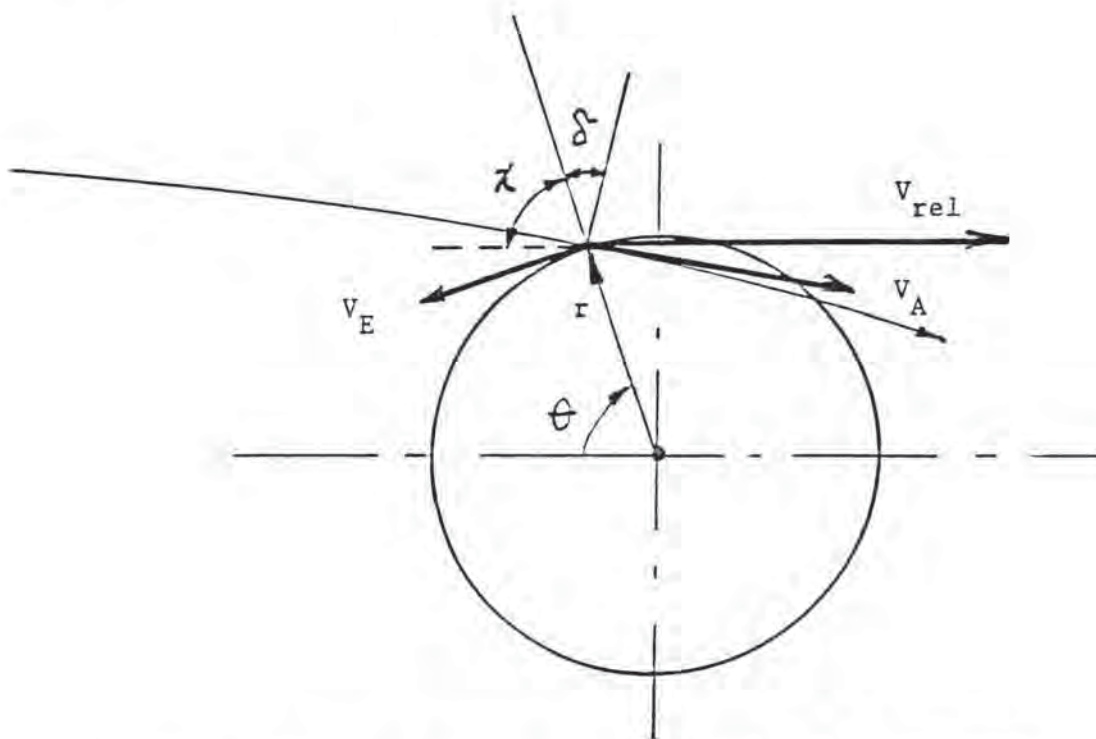


Fig.2. Interstellar atom trajectory in the interplanetary space. Angle δ is the angle between the normal to atom velocity V_A and radius-vector r . Angle χ is the angle between the vector of the atom velocity $V_{rel} = V_A - V_E$ relative to observer moving with the Earth and radius-vector r .

good approximation for the characteristics of neutral interstellar atoms at angles $\theta < 150^\circ$ (angle θ is counted from the direction antiparallel to the relative velocity vector). Another important common assumption is that interstellar atoms move independently along Keplerian orbits under the forces of solar gravitational attraction and radiation pressure. For an optically thin medium both the radiation force and that of solar gravitation are inversely proportional to the square of the distance from the Sun. Hence, the radiation force can be taken into account by introducing the "effective" gravitational constant equal to $G(1 - \mu)$, where μ is the ratio of the radiation to gravitational forces and its value depends strongly on the type of the atoms. Interstellar atoms are ionized (i.e. are lost for our purpose) by solar radiation and by charge exchange with the solar wind ions. The ionization rate is assumed to be inversely proportional to the square of the distance from the Sun and equal to $\beta(R) = \beta_0 (R_0 / R)^2$ where β_0 is the ionization rate at the Earth's orbit.

It is convenient to describe trajectories of individual interstellar atoms (*Fahr, 1968*) in polar coordinates

$$r = \frac{\gamma p_0^2}{1 + \gamma p_0 \sin \theta - \cos \theta} \quad (1)$$

where r and θ are the polar coordinates of the particle, p_0 is the "impact parameter" of the atom reaching the given point (r, θ) , $\gamma = V_0^2 / (G(1 - \mu) M_s)$. Two possible trajectories lead to the point (r, θ) - a direct trajectory with the polar angle θ changing less than 180° on the way from infinity and an indirect one with the polar angle changing more than 180° (fig.1). Two different impact parameters p_0 correspond to these two trajectories leading to the same point (r, θ) and they are equal to

$$p_0 = \pm r \sin \theta / 2 + (r(1 - \cos \theta) / \gamma + r^2 \sin^2 \theta / 4)^{1/2} \quad (2)$$

The highest possible relative velocity between interstellar atom and the observer moving with the Earth is preferable for the detection of atoms, as will be shown. This fact, as well as the dependence of atom survival probability on angle θ , will limit our consideration to

the direct flux only in the region $\theta < 180^\circ$.

From the continuity law, one easily obtains that the number density of interstellar atoms at a given point (r, θ) is

$$n(r, \theta) = \frac{p_0 n_0 V_0 S(r, \theta)}{r V_A(r) \sin \theta \cos \delta} \frac{dp_0}{dr} \quad (3)$$

where n_0 is the number density of unperturbed interstellar atoms (at infinity), $V_A(r) = (V_0^2 + 2G(1-\mu)M_S/r)^{1/2}$ is the velocity of an atom at a distance r from the Sun, δ is the angle (fig.2) between the normal to the atom velocity vector and radius-vector to the point (r, θ) , $S(r, \theta)$ is the probability for the atom to survive along the trajectory.

From equation (1), one obtains

$$\frac{dp_0}{dr} = \frac{H^2}{(2\gamma p_0 H - \gamma^2 p_0^2 \sin \theta)} \quad (4)$$

where $H(r, \theta) = 1 + \gamma p_0 \sin \theta - \cos \theta$. Angle δ can be calculated from

$$\operatorname{tg} \delta = (1/r) (dr/d\theta) \quad (5)$$

and, as it follows from equation (1),

$$dr/d\theta = -\gamma p_0^2 (\gamma p_0 \cos \theta + \sin \theta) / H^2 \quad (6)$$

The probability for an atom to survive on its way from infinity to point (r, θ) is

$$S(r, \theta) = \exp(-\beta_0 R_0^2 \theta / p_0 V_0) \quad (7)$$

The angle χ between the vector of the atom velocity $V_{rel} = V_A - V_E$ relative to an observer moving with the Earth and the radius-vector to the point (r, θ) can be calculated from simple geometrical considerations (fig.2).

The differences in radiation pressures and ionization rates leads to the differences in the populations of interstellar atoms in interplanetary space. For helium and oxygen atoms, one can neglect the radiation pressure (i.e. $\mu = 0$) but for hydrogen and deuterium the radiation pressure substantially counterbalances the force of solar gravitation. We assume here that the ratio of the radiation force to gravitation is **0.8** for hydrogen and **0.4** for deuterium atoms. For hydrogen molecules, the radiation pressure is assumed to be negligible.

For helium, the ionization rate is determined mostly by solar EUV radiation and we assume it equal to $0.8 \cdot 10^{-7} \text{ s}^{-1}$ at the Earth's orbit. For hydrogen and deuterium, charge exchange with the solar wind protons becomes more important accounting for approximately two thirds of the ionization rate, and we assume here that the total ionization rate is equal to $5 \cdot 10^{-7} \text{ s}^{-1}$ at the Earth's orbit. Ionization of hydrogen atoms by two-step photoionization (*Gruntman, 1990a*) becomes important in the areas close to the Sun only and will be disregarded. For oxygen atoms, both charge exchange with solar wind protons and photoionization by solar photons are important, and the total ionization rate at the Earth's orbit is estimated to be $5 \cdot 10^{-7} \text{ s}^{-1}$ (e.g. *Cummings and Stone, 1990*). The ionization rate of hydrogen molecules is assumed equal to $5 \cdot 10^{-7} \text{ s}^{-1}$ (*Holzer, 1977*). Further, all calculations are performed for the observer moving together with the Earth along its orbit around the Sun.

3. FLUXES OF INTERSTELLAR ATOMS AT THE EARTH'S ORBIT

The calculated dependence of velocity and energy of atoms on the angle θ is shown in fig.3. For interstellar hydrogen molecules and oxygen atoms, the velocity is the same as for helium atoms and the energy is a factor two smaller and a factor of four larger correspondingly. In fig.4 the dependence of angle χ between vector of relative velocity V_{rel} and radius-vector r on the angular position along the Earth's orbit θ for interstellar hydrogen, deuterium and helium atoms is presented. Again, interstellar hydrogen molecules and oxygen atoms have the same dependence as helium atoms. The dependence of the fluxes number densities of interstellar atoms (normalized to corresponding fluxes number densities in unperturbed ISG far away from the Sun) on the angular position θ along the

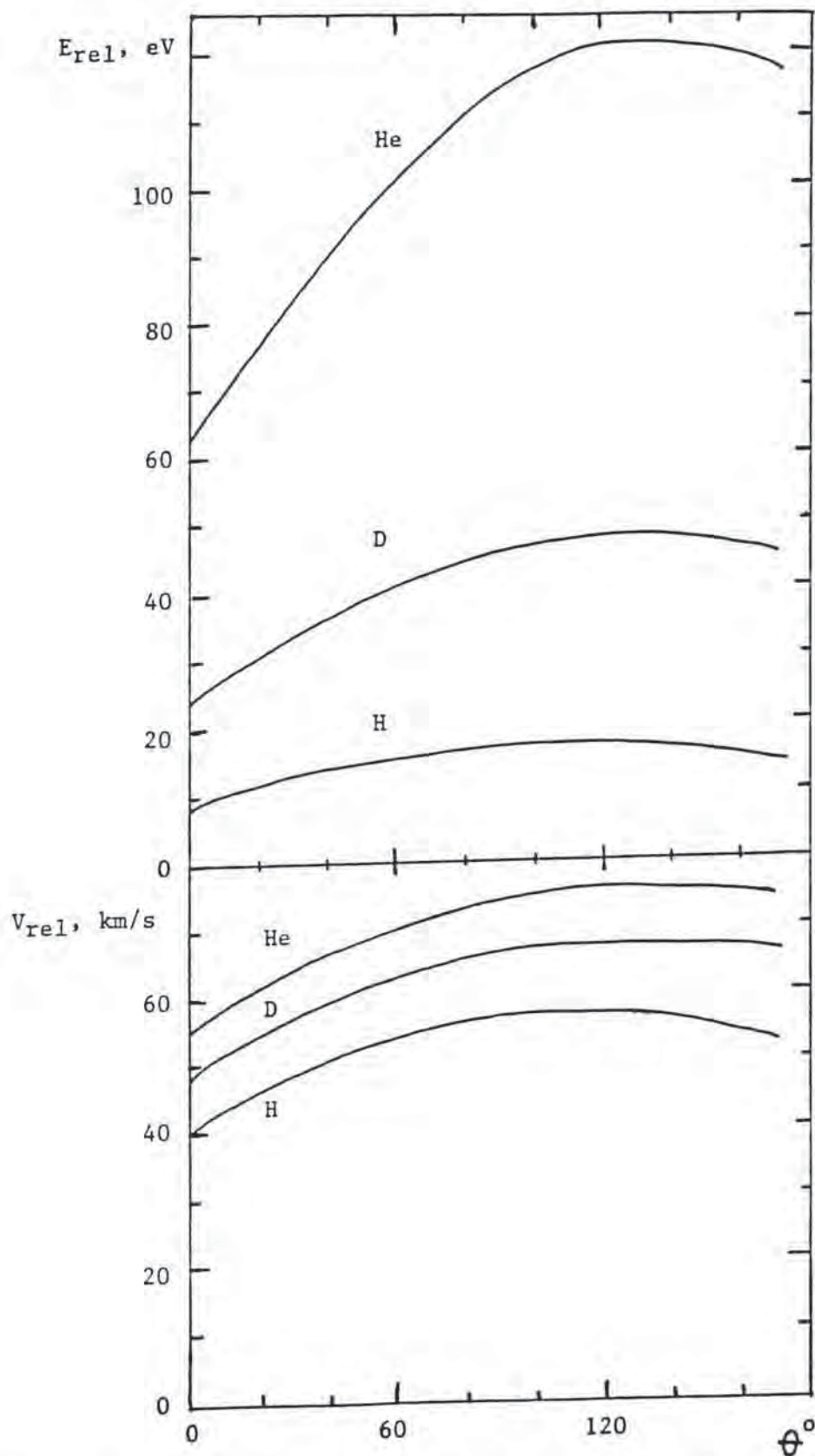


Fig.3. Dependence of velocity and energy relative to the observer moving with the Earth on the angle θ for interstellar hydrogen, deuterium, and helium atoms. For interstellar hydrogen molecules H_2 and oxygen atoms O , the velocity is the same as for helium atoms and energy is a factor two smaller and a factor of four larger correspondingly.

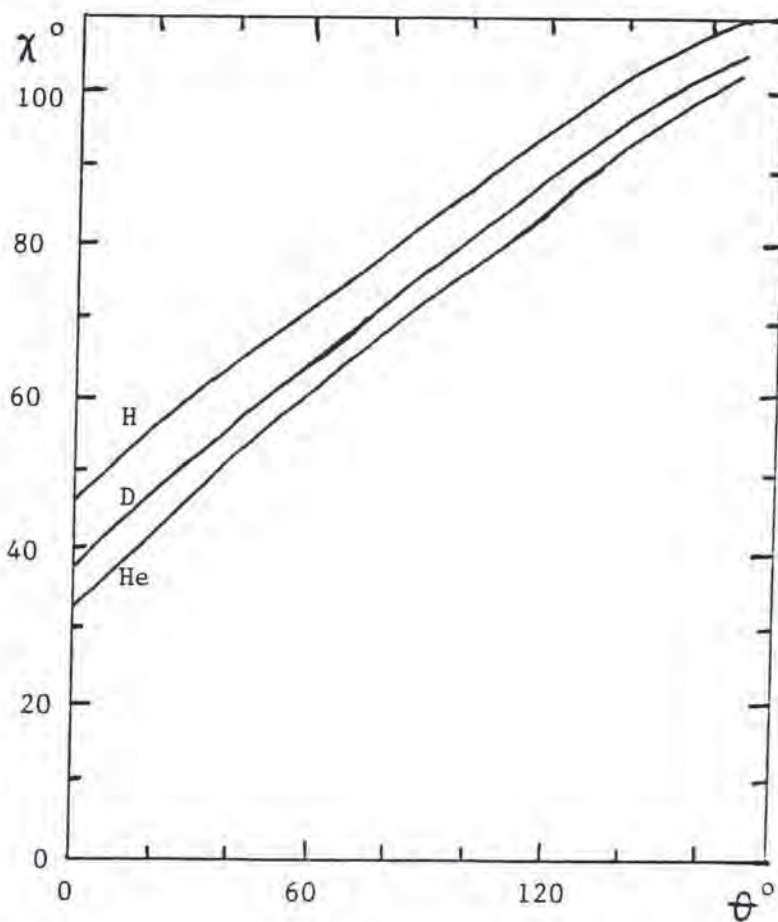


Fig.4. Dependence of angle χ between vector of relative velocity V_{rel} and radius-vector r on the angular position along the Earth's orbit θ for interstellar hydrogen, deuterium and helium atoms. Interstellar hydrogen molecules and oxygen atoms have the same dependence as helium atoms.

Earth's orbit is shown in fig.5.

It is important to note that deuterium atoms have not only higher relative velocities than hydrogen atoms but also they are expected to come from a direction which is different ($6 - 10^\circ$) from that of hydrogen atoms. Also from different direction come interstellar hydrogen molecules as well as oxygen atoms. The spread of the angles at which atoms are coming to a given point would be determined by the temperature of ISG T_0 . This spread is different in the ecliptic plane and in the direction normal to the ecliptic (e.g. *Wallis and Hassan, 1978; Gruntman, 1980*). The value of the angular spread in ecliptic plane can be easily roughly estimated from the fig.4. Characteristic thermal velocity of hydrogen atoms (in a direction perpendicular to the velocity vector V_0) with the temperature $T_0 = 10^4$ K is **9 km/s** which corresponds to the scatter of the angles θ of "incidence" of atoms $\pm 25^\circ$. Such scatter in angles (i.e. at initial angles θ) at the position of observer at, say, $\theta = 120^\circ$ would result in the scatter of the angles χ of coming of the atoms within $\pm 10^\circ$. Thermal velocity component, which is parallel to velocity vector V_0 , would also contribute to the scatter of the angles χ , though to a much smaller extent. Obviously, deuterium atoms would be confined within smaller angular range ($\pm 7^\circ$ at $\theta = 120^\circ$) than hydrogen atoms. These differences in kinematic characteristics as well as dependence of expected fluxes of hydrogen and deuterium on angle θ (fig.5) would determine that for an instrument with a certain field of view one can expect the ratio of deuterium-to-hydrogen fluxes to be enhanced up to a factor of ten (depending on the position and on the direction of observation) as compared with that ratio at infinity in unperturbed ISG. The same is valid also for the ratio of the flux of hydrogen molecules to that of hydrogen atoms. The scatter in initial angles of incidence θ would be only $\pm 6^\circ$ for oxygen atoms which would transfer in the scatter of the angles χ equal to $\pm 3^\circ$ only. For realistic number densities of interstellar gas major constituents at the LISM - $n_H = 0.1 \text{ cm}^{-3}$ and $n_{H_2} = 0.01 \text{ cm}^{-3}$ - one can expect that number densities of deuterium and oxygen atoms would be of the order of $n_D = 10^{-6} \text{ cm}^{-3}$ and $n_O = 10^{-4} \text{ cm}^{-3}$ correspondingly. As far as the number density of hydrogen molecules is concerned, the situation is uncertain and one can even expect that they may constitute a substantial part of interstellar gas in the LISM. The total fluxes of the atoms in the LISM, that are used to normalize the expected values of fluxes at the

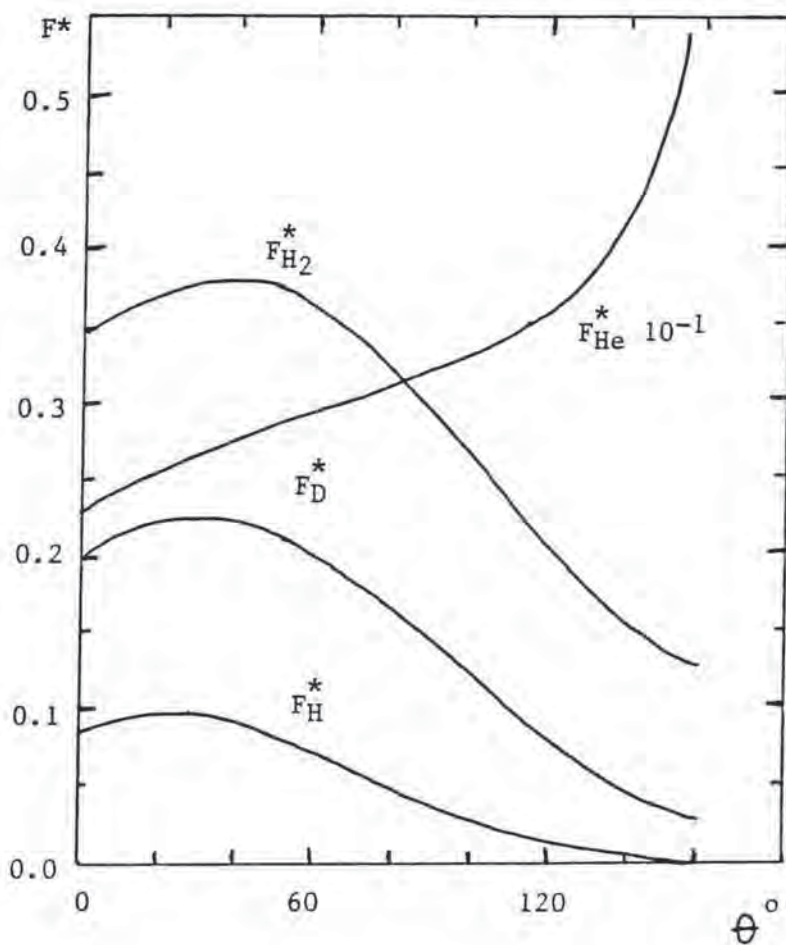


Fig.5. Dependence of the fluxes of interstellar neutrals (normalized to flux number density in unperturbed ISG far away from the Sun) on the angular position θ along the Earth's orbit. Note that helium flux must be multiplied by a factor 10. Normalized flux of interstellar oxygen atoms is equal to that of helium.

Earth's orbit in fig.5, are then the following

$$F_H = n_H V_0 = 2 \cdot 10^5 \text{ cm}^{-2} \text{ s}^{-1}$$

$$F_D = n_D V_0 = 2 \text{ cm}^{-2} \text{ s}^{-1}$$

$$F_{He} = n_{He} V_0 = 2 \cdot 10^4 \text{ cm}^{-2} \text{ s}^{-1}$$

$$F_O = n_O V_0 = 2 \cdot 10^2 \text{ cm}^{-2} \text{ s}^{-1} .$$

The important result of the presented calculations is that expected fluxes number densities ($\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) of different interstellar atoms would depend in a different ways on position and direction of the observation. This fact should allow to determine in unambiguous way the composition of the ISG from the measurements performed at the Earth's orbit. It is highly desirable to detect and to determine kinematic characteristics of interstellar neutral atoms during one year period of time while "travelling" with the Earth along its orbit around the Sun.

There is also another flux of energetic neutral atoms (ENAs) in interplanetary space, which could be considered in a first approximation as a close to uniform, - the flux of energetic "secondary" atoms born in the interaction (charge exchange process) of interstellar gas with the solar wind in heliospheric interface region. The solar wind is a highly supersonic plasma flow into the LISM which is characterized by a certain finite pressure (magnetic field + cosmic rays + thermal motion of atoms, ions and electrons). Therefore, this supersonic plasma flow has to stop and its kinetic energy has to be converted into the energy of thermal motion of plasma ions and electrons. Details of the interaction depend essentially on the assumed parameters of the LISM. What is important is that there has to be a very hot plasma at this region. Neutral interstellar gas atoms penetrate relatively freely through the interface region and there is a certain probability for "hot", energetic (> 100 eV) ions to charge exchange with interstellar gas atoms and give rise to the ENAs. The velocities of these particles would reflect velocity distribution of ions and some of them would be directed back towards the Sun. The estimates show that the energy of such atoms would be in the range of 100 - 800 eV and flux number density - $3 \cdot 10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (*Gruntman, 1990b*).

4. HOSTILE BACKGROUND AND EXPERIMENTAL CONDITIONS

The expected neutral atom number densities are very low - much less than 10^{-1} cm^{-3} - therefore any conventional experimental technique, based on ionization of the neutral atoms and subsequent analysis and detection of the positive ions, is not applicable. However, the energy of atoms may be sufficient to produce secondary emissions while bombarding sensitive/conversion surfaces. The interplanetary space is characterized by a high level of the background radiation of the UV/EUV photons, which produce also photoemission and may trigger detectors with a rather high efficiency. The majority of background photons are in hydrogen Lyman-alpha line (1216 \AA) with flux equal to **300-600 R** ($1 \text{ R} = 1 \text{ Rayleigh} = 10^6 / 4\pi \text{ phot cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) and in helium resonance line (584 \AA) with flux **1-10 R** at the Earth's orbit.

Experimental conditions really present a challenge and can be summarized as following:

1. Fluxes of interstellar atoms are not omnidirectional but are confined within certain solid angles whereas fluxes of ENAs and background photons are of a diffuse type;
2. The neutral atom fluxes are much smaller than that of photons and as a consequence the expected count rates of detectors (based on secondary electron emission) due to background photons would be much greater than those due to atoms;
3. The absolute values of the neutral atom fluxes are very low, however long exposures, up to days and even weeks, to accumulate a signal are possible.

No wonder there were no experiments in the past to measure *in situ* neutral atoms in interplanetary space !

The only present on-going attempt to detect *in situ* neutrals in space is the experiment on **Ulysses** mission (launched in October 1990) to study interstellar helium atoms (*Rosenbauer et al, 1983, 1984*). The instrument uses the secondary electron and ion emissions from the specially prepared surface (**LiF**) due to bombardment of helium atoms. The only other attempt to detect directly *in situ* neutrals (utilizing ultrathin foil and coincidence technique) - ENAs from heliospheric interface - will be carried out by **Relikt-**

2 mission (*Gruntman and Leonas, 1986; Gruntman et al, 1990*) in 1993, providing the Soviet space program does not collapse completely by that time. Both utilized techniques will not work, however, for the registration of other interstellar atoms. The application of a coincidence technique for the detection of relatively high energy atoms as helium and oxygen, as was proposed for a modification (*Gruntman, 1989, 1990b*) of the abovementioned interstellar helium direct detection instrument, has very low detection efficiency and may require unacceptably long accumulation times. The only feasible experimental approach to cope with the above conditions is to arrange the instrument in such a way that neutral atoms interact with sensitive/conversion surface absolutely differently from that of photons, and neutral atoms are registered with a relatively high efficiency. Moreover, the instrument to study *in situ* neutral atoms must also identify the incoming particles (measurement of atom mass and/or velocity or energy is required) as well as suppress noise counts due to stray photons and particles.

5. NEW DETECTION APPROACH

The proposed approach is based on the conversion of particles to be measured to negative ions and subsequent analysis and detection of these ions. It is important that negative ions are not present in ambient solar wind plasma in interplanetary space - hence they are unique in a sense that they are born due to interaction of incoming neutral flux with a specially prepared conversion surface only. Such a conversion technique is rather well developed in the laboratory applications for the production of high intensity negative hydrogen/deuterium ion beams which after stripping are used for fusion plasma energy pumping. The conversion on surfaces to negative ions for energy analysis of hydrogen atoms (emitted by fusion plasmas, i.e. for plasma passive corpuscular diagnostics) was suggested by *Massmann et al, 1979*. Later the same possible application was emphasized by *Van Wunnik and Los, 1983* and *Schneider et al, 1983*. The use of this technique for direct detection of interstellar hydrogen atoms was first proposed by *Gruntman and Leonas, 1983* and discussed later in some detail by *Gruntman, 1990b*.

Neutral hydrogen atoms after collision/reflection with certain types of surfaces

acquire with a relatively high efficiency the negative charge, i.e. become negative ions. The efficiency of such a conversion depends on the type of the atom, atom initial velocity, angle of incidence, and the type of surface with which it interacts. Only those atoms, which can form negative ions, can be studied by the proposed approach. This is the reason why such abundant interstellar gas constituent as helium and such relatively abundant traces as nitrogen and neon can not be measured by the proposed technique.

The negative ions, and hence the incoming neutral atoms, could be identified, i.e. their mass could be reliably determined by appropriate particle analyzer. The use additionally of a time-of-flight (TOF) analyzer could be helpful because it would provide not only independent particle identification but also negative ion detection in a coincidence mode which eliminates the problem of the background count rates of detectors due to stray photons and particles within the instrument. The latter feature is of great importance because fluxes of such interstellar gas constituents as oxygen and especially deuterium are extremely low and essentially noise-free "assured" detection is crucial for long accumulation times.

The possibility to apply proposed technique to the study of planetary upper atmospheres and exospheres is briefly discussed in the **Appendix**.

6. INSTRUMENT

6.1 General scheme

A possible simplified version of the instrument is shown schematically in fig.6. A final design of the instrument will depend, obviously, on the results of laboratory experiments and specific requirements of the space mission. The scheme, presented here, as well as the following discussion of requirements to and performance of instrument elements, serve the purpose to illustrate the key principles that will be retained in any particular design of the instrument of such kind.

Charged particles - ions and electrons - are prevented from the entering the instrument by electrostatic or permanent magnet deflection system (not shown). The deflection system constitute a part of the instrument baffle which determines its field of view. Interstellar neutral atoms hit the sensitive/conversion surface (CS) and are

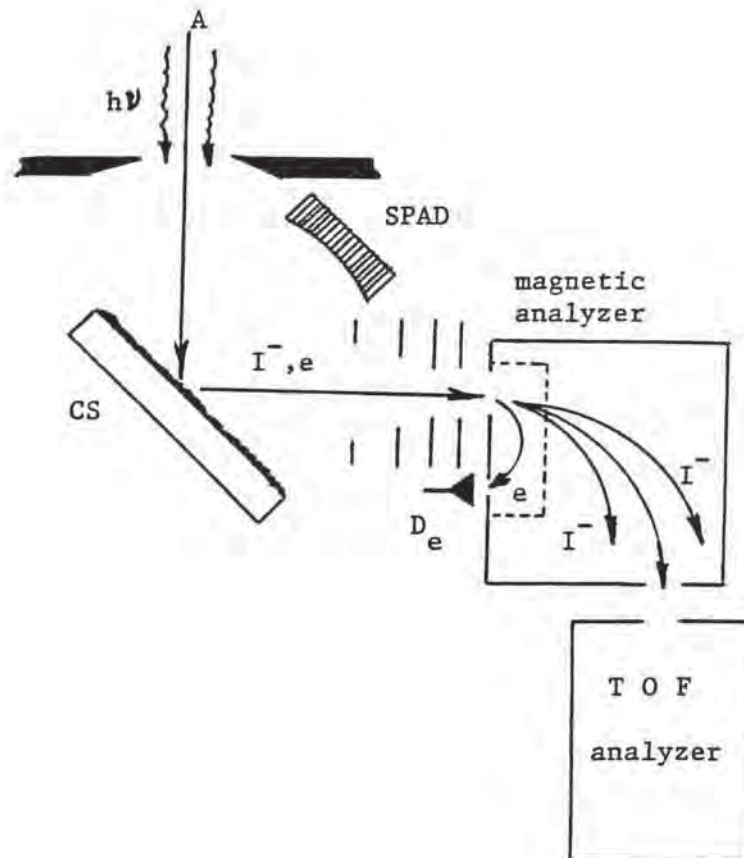


Fig.6. Possible version of the instrument to measure fluxes of neutral atoms of interstellar origin. Neutral atoms (A) are converted impinging on the conversion surface (CS) to negative ions I^- . Atoms and background photons ($h\nu$) produce also secondary electrons (e). Negative ions and electrons are accelerated and focussed by the electrostatic lenses, then they are separated in a magnetic analyzer according to their masses. Electrons are registered by electron detector D_e and ions are additionally analyzed and registered by TOF analyzer. Surface preparation and activation device (SPAD) serves to maintain the required quality of conversion surface. Dashed line confines the region with the smaller magnetic field.

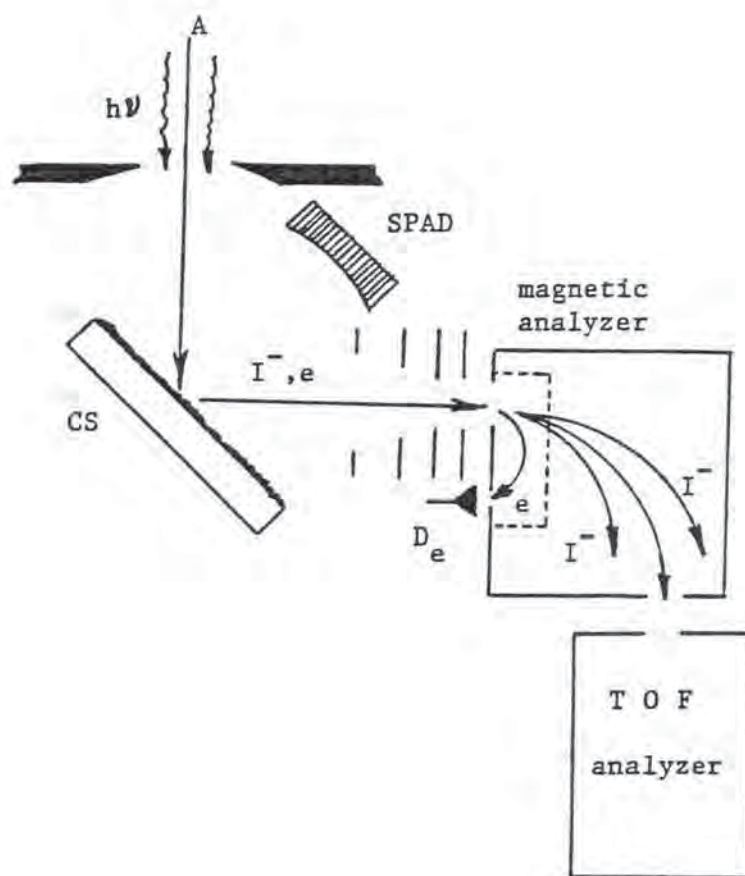


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converted with certain probability to negative ions. Background UV photons as well as atoms also would produce secondary electrons with high efficiency. Negatively charged particles (ions and electrons) are accelerated up to a fixed energy (say, 10 keV) and are separated according to their masses in a simple magnetic analyzer. Negative ions which originate after interaction with a conversion surface are unique (in a sense that there are no other sources or processes which could produce negative ions) and can be "assuredly" detected with essentially negligible noise by a coincidence technique.

Electrons are registered by a separate electron detector (channel electron multiplier) D_e . Measurement of electron count rate provides a simple monitor of the conditions on a conversion surface. Most of the electrons would be emitted due to background UV photons with a known flux and one can expect that photoelectron emission would depend, obviously, on the conditions of the surface. Then negative ions enter a simple TOF section. Depending on acceleration voltage, negative ions of different masses would pass through magnetic analyzer with a constant field and would reach the entrance aperture of a TOF analyzer where they would be analyzed and detected. The TOF analyzer would measure velocities of the particles. Special surface preparation and activation device (SPAD) - its type still has to be determined - would be used to refresh and/or to activate conversion surface. Another possible scheme of instrument may comprise up to three independent TOF analyzers which would measure all three expected species of negative ions (H^- , D^- , and O^-) in parallel, simultaneously. In any case, negative ions of a selected mass would be separated from other particles and detected (and their velocity measured) by a dedicated TOF analyzer. In principal, only one analyzer section (magnetic or TOF) is required to separate ions of different masses and the same energy. However, one of the purposes of the experiment is to measure traces - deuterium and oxygen atoms - which constitute very small fraction (10^{-4}) of predominant flux of hydrogen atoms. Therefore, even small flux of stray particles (say, negative hydrogen ions reflected from some surfaces) could result in instrumental artefacts which would obscure completely the presence of traces. The proposed scheme with double analyses - magnetic and TOF - should provide assured, essentially noise-free detection and identification of negative ions and hence incoming neutral atoms.

6.2. Conversion surface

Different surfaces can serve as converters to negative ions, however the highest conversion efficiencies are characteristic for surfaces with a low work function and a high density of electron states at the Fermi level. The most developed and well studied conversion surfaces are metals covered by alkali layers, e.g. by cesium.

Atom conversion to negative ions is generally described by electron tunneling to the atom which moves classically. The negative hydrogen ion yield is a convolution of the reflection coefficient and the charge transfer probability. The affinity level of the atom approaching the metal surface is gradually shifting due to attractive interaction with its image charge in the metal, as shown in fig.7 (*Van Amersfoort et al, 1985*). At a certain distance from the surface the shifted affinity level crosses that of the work function of the metal. Then metal electrons can tunnel to and be captured by the atom.

The initially sharp affinity level of the atom is broaden into a band of a finite width. The distance from the surface, at which electrons could be captured, constitute, for example, $6 - 8 a_0$ (a_0 is a Bohr radius) for a partially cesium covered tungsten (*Van Wunnik, 1983a*). After reflection from the surface, on the out-bound leg of particle trajectory, when affinity level becomes again higher than the work function level, the electron may tunnel from the negative ion back to the empty metal states. Such model corresponds to zero temperature of the conversion surface and conversion of the atom to negative ion has an energy threshold equal to the difference between the work function and unperturbed affinity energy (*Seidl et al, 1989*). If converter temperature is not zero, then the electron distribution is smeared around the Fermi level (e.g. *Cui, 1991*). This level smearing as well as broadening of the affinity level of the ion would allow electrons to tunnel both ways when particle is within a certain range of distances from the surface, which would result in lowering of effective energy threshold for a conversion.

There is a certain probability that particle leaves the surface as a negative ion. Knowing electron transition frequency, it is possible to calculate the equilibrium probability for the atom to be negatively charged at a certain distance from the surface. Introducing further motion of the atom (described classically) and integrating the rate equation, one can

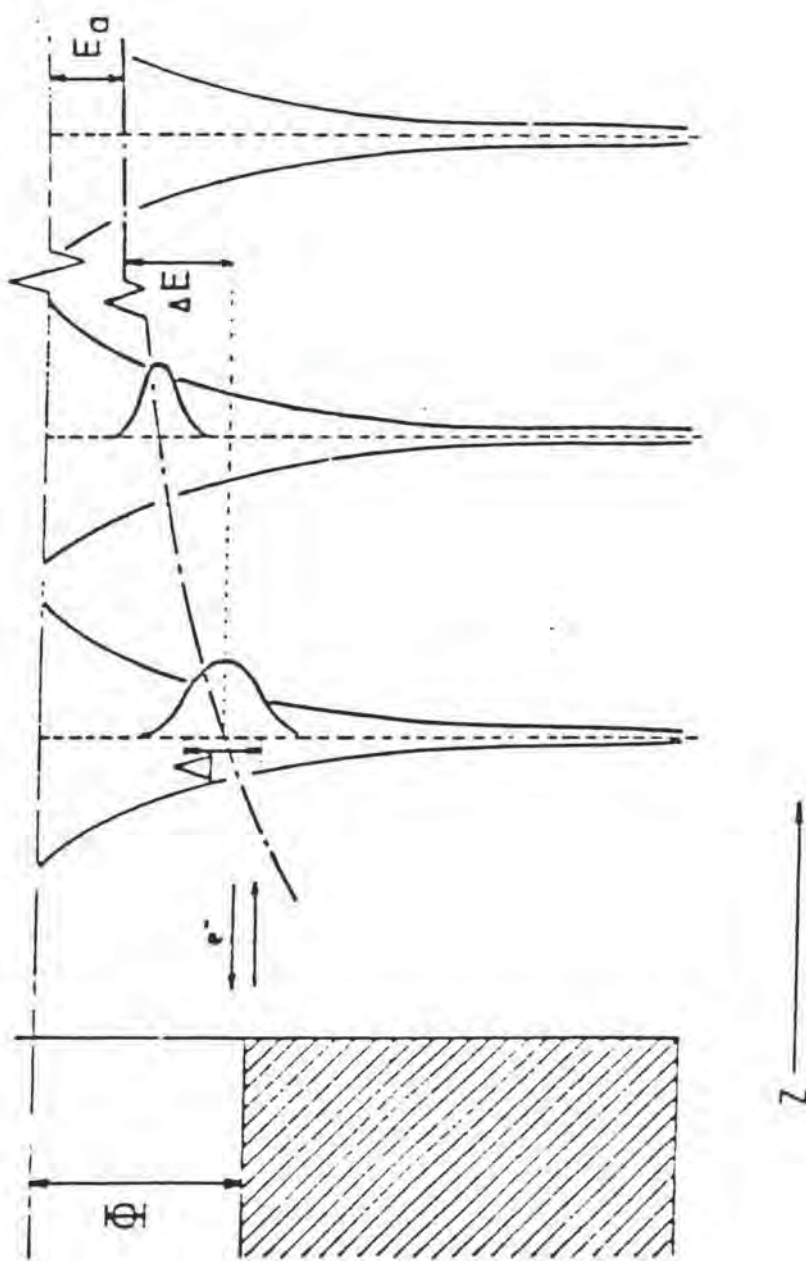


Fig.7. Energy diagram of a static hydrogen atom at a distance z from a metal surface. The work function is denoted as Φ . The metal electrons have energies up to the Fermi level, which is Φ eV below the vacuum level. For large z the atomic affinity level is E_a eV below the vacuum level. In the vicinity of the metal the affinity level is shifted and broadened. From: *Van Amersfoort et al, 1985*.

determine the probability that the atom leaves the surface as a negative ion. The charge transfer probability depends on both components of the atoms velocity, parallel and perpendicular to the surface. Typical velocity of interstellar atoms is much smaller than electron velocities in conversion surfaces, therefore the charge transfer probability is determined mostly by the atoms velocity component normal to the surface (*Van Wunnik et al, 1983a*). As an example, the calculated dependence (from *Van Os et al, 1988*) of negative ion formation for hydrogen atoms (for three different surfaces) on normal energy is shown in fig.8. For convenience, the correspondence between velocity and energy of atoms is presented in fig.9.

Let us assume that interstellar hydrogen (or deuterium) atom normal velocity is **35 km/s**, which corresponds to **45°** angle of incidence on conversion surface for an atom with the total velocity **50 km/s**. Then the fraction of negative ions in the particles reflected from the tungsten surface **W(100)** covered by a thick layer of cesium, is **5 - 7 %**. A very thin cesium layer (half a monolayer) may give much higher negative ion fraction (*Van Wunnik et al, 1983a*), however, from a practical point of view, to maintain such a surface in a space instrument may be too difficult and the use of thick cesium layer seems to be preferable. Overall conversion coefficient of **several per cent** (*Schneider et al, 1981; Van Wunnik et al, 1983b; Van Os et al, 1988*) could be expected for interstellar hydrogen and deuterium atoms.

Work function of the surface is very sensitive to the degree of the coverage by cesium. For example, the detailed study of **n-type (100)** silicon substrate shows that a clean surface has a work function **4.75 eV**, surface covered by a monolayer of cesium - **2.00 eV**, and surface covered by a half of a monolayer of cesium - **1.47 eV** (*Souzis et al, 1989*). Controlled oxidation of the cesium may lead to further lowering of the work function down to **0.9 eV**. For thick layers of cesium, which means that substrate may not be crucial, work functions of the order of **1 eV** are reported (*Souzis et al, 1989; Melnychuk and Seidl, 1991*). Sputtering and implantation processes are unimportant for low energy neutral atoms, as in our case, and complex multi-component converters such as cesium oxides - mixture of **Cs/Cs₂O/Cs₂O₂** - can be used. Such promising surfaces can be several hundred angstrom

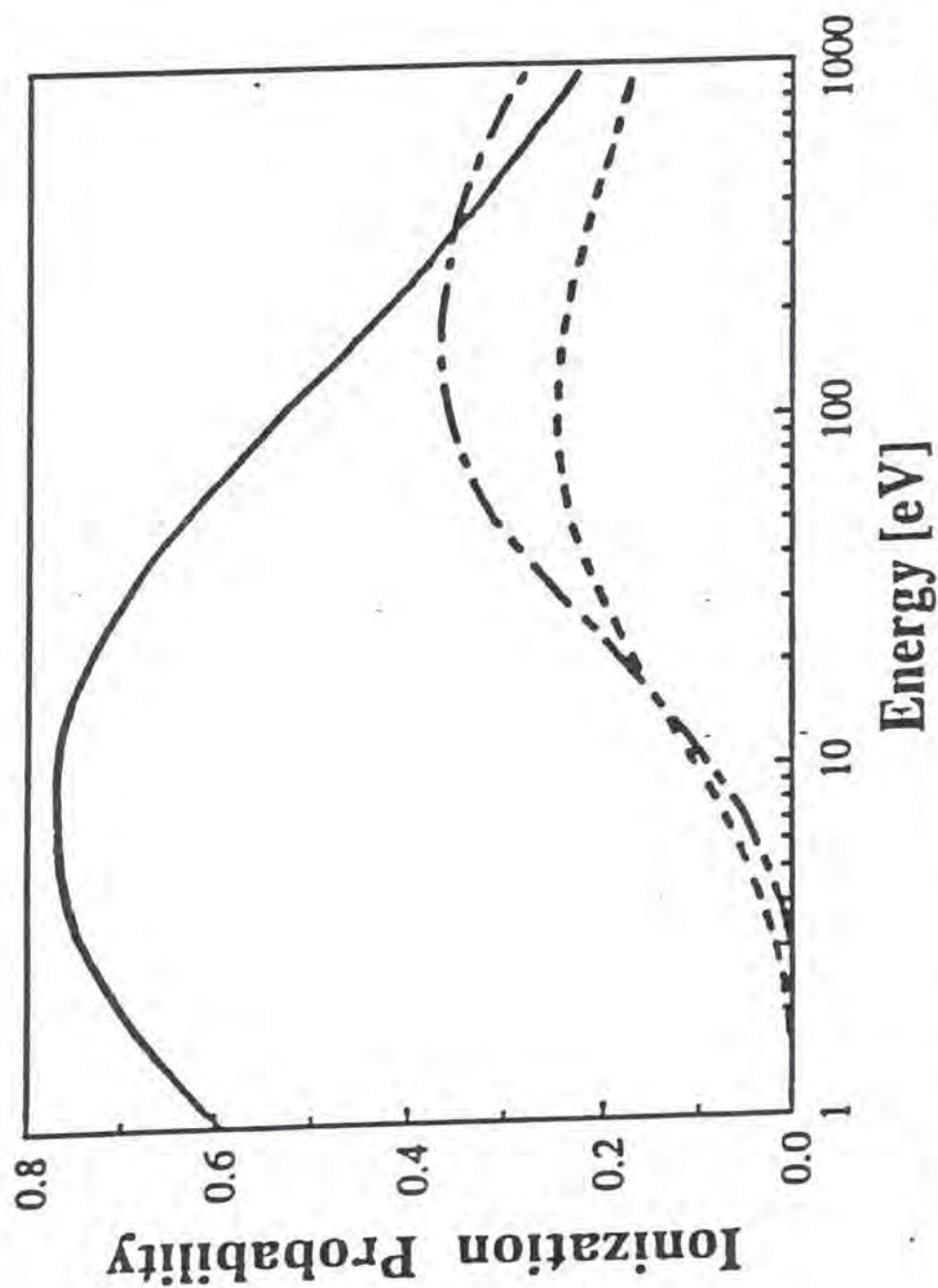


Fig.8. Calculated negative-ion formation probability for hydrogen atoms leaving the surface along the normal vs energy. The solid line is for half a monolayer cesium coverage, the dashed line is for a full monolayer cesium coverage, and the chain-dashed line for a thick barium coverage of the W(110) surface. From : *Van Os et al, 1988*

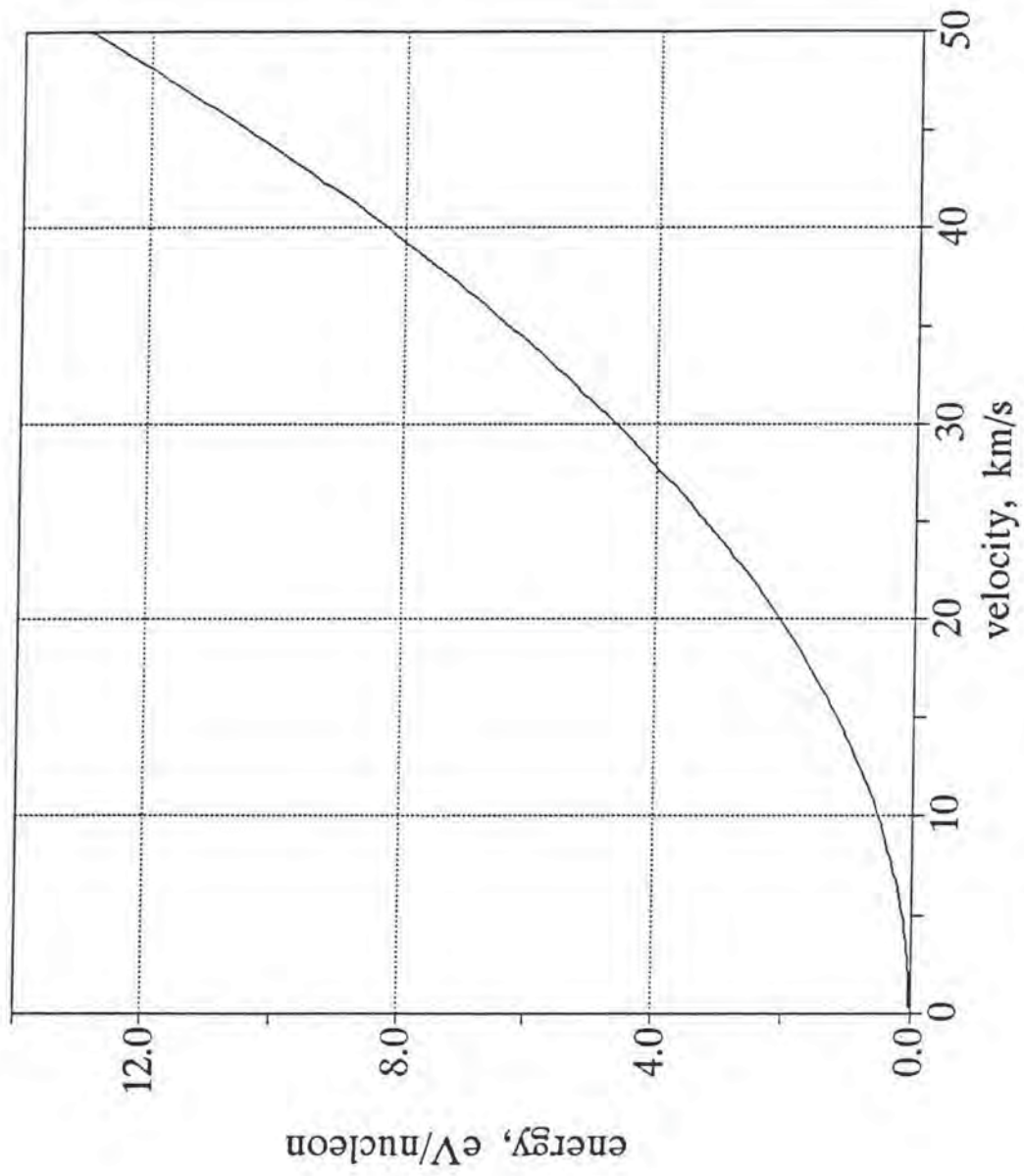


Fig.9. Dependence of the energy of atom on its velocity.

thick, their work function is independent of the substrate composition, and cesium oxides have vapor pressure much lower than the pure cesium (*Melnychuk and Seidl, 1991*). An exposure of oxygenated cesium surfaces to large fluxes of hydrogen may result in some change, about ± 0.1 eV, of work function (*Souzis et al, 1989*).

Photoemission properties of the conversion surface would depend strongly on its work function. The measurement of photoelectron flux from such surface is a direct way to determine the value of work function when the photon flux and its spectral distribution are known. Such measurements will be used in flight instrument to monitor conditions on the converter surface.

Cesiated surfaces, though providing high conversion efficiencies, create a lot of problems due to a capricious behaviour of cesium. For example, cesium has a high vapor pressure which could lead to contamination of the instrument. Metal surfaces covered by layers of alkalis other than cesium, such as Na (*Schneider et al, 1983*) or Rb and K (*Schneider et al, 1981*) can also be used for conversion of hydrogen atoms.

Last time, a lot of attention was devoted to barium surfaces (e.g. *Van Os et al, 1987, 1988; Kleyn, 1990*) which also may provide high conversion efficiencies. Barium is a much more stable and convenient material to use though initial activation - by heating up to 1200 K (*Melnychuk and Seidl, 1991*) or sputtering of the barium surface - is needed to eliminate oxide layer and provide metal-type surface. Interesting possibility is to use ambient space plasma (e.g. solar wind plasma) to sputter sensitive/conversion surface: plasma ions could be sucked in, focussed and accelerated for such a purpose. However, it may require a couple of days of sputtering to accumulate necessary dose. Another possible surface under the study is LaB₆ (e.g. *Kleyn, 1990*) which also require the heating to the high temperature 1400 K to activate such a conversion surface. Different metals, such as W and Mo (e.g. *Van Bommel et al, 1984*) and Mg and Cu, also may serve as a conversion surface, however typical conversion efficiencies are usually very low - 10^{-4} - 10^{-5} . Certainly the selection of the type of conversion surface and a way to activate and control it as well as the stability of the surface and the necessity to refresh (and/or to activate) it during long duration space flight require further detailed study. This problem obviously constitutes

presently the less clear part of the proposed technique/instrument. However, one may safely assume as a conservative estimate for interstellar hydrogen and deuterium atoms the value of $\epsilon_{\text{H}} = 0.01$ for such a conversion coefficient.

It should be noted here that almost all experimental data available are for hydrogen and its isotopes (hydrogen molecule could be considered as two independent hydrogen atoms). Electron affinity of oxygen atom is rather high - 1.45 eV as compared with 0.75 eV for hydrogen (e.g. *Radzig and Smirnov, 1985*) and one can expect that oxygen atoms will be even more efficiently converted to negative ions. For cesiated surface the affinity energy is larger than a work function, which means that there is no energy threshold for a conversion, and oxygen atoms are converted with the efficiency of 0.67 (*Van Pijsteren et al, 1989*). Experimental data on oxygen conversion are limited and a special study is absolutely necessary (work with the oxygen beams is notoriously plagued by difficulties due to reactivity of oxygen).

Potential problem with conversion on the surface, that should be kept in mind, is the possibility to produce negative ions by sputtering previously adsorbed atoms and molecules from the surface. This is one of the reasons that surface has to be clean and possibly prepared and/or activated in space. Sputtering of negative ions may be especially important for measurement of oxygen since oxygen is always could be found on surfaces exposed after preparation to the atmosphere. Energetic ions with the energy, say, higher than 100 - 200 keV, would pass the deflection system at the entrance of the instrument and would hit the conversion surface sputtering negative ions. The flux of such energetic ions, even at quiet conditions on the Sun, is not less than $1 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in interplanetary space. Ions from terrestrial magnetosphere would also contribute to this effect.

Adsorption of interstellar atoms on the conversion surface does not pose a problem. Even for the most intense expected flux of interstellar hydrogen, it would take 15 years to cover one per cent of the sensitive surface by hydrogen providing each impinging atom is adsorbed. The most of the contamination danger may come from the adsorption of atoms and molecules outgassed from the instrument elements and the spacecraft itself.

6.3 Magnetic analyzer

Magnetic analyzer (fig.6) serves two purposes: i) to separate electrons from negative

ions and to direct them to electron detector D_e , and ii) to separate negative ions of the required mass and to direct them to exit slit for subsequent analysis and registration by TOF unit. These requirements could be met by a non uniform magnetic field. Magnetic analyzer can contain two separate regions with two different magnetic fields: say, $B_1 = 200$ Gauss and $B_2 = 2000$ Gauss. Such fields could be easily created by rare earth (e.g. CoSa) permanent magnets. Then negative ions would pass the first region, which is confined within dashed lines in fig.6, almost without changing their trajectories whereas electrons would be directed toward electron detector D_e . Electron detector count rate would serve to monitor conditions on the conversion surface. The radius of electron trajectories would vary from 2.1 cm and 1.5 cm for electron energies between 16 keV and 8 keV correspondingly (these energies are selected just as an example). Electrons with such a difference in trajectories could be easily focussed and registered by the same detector D_e . If magnetic analyzer is adjusted to pass to exit slit hydrogen ions with the energy 16 keV, which corresponds to the trajectory radius 9.1 cm, then deuterium ions would pass it with the energy 8 keV. For a real instrument, the exact energies required for the passage of the ions, as well as analyzer energy resolution, should be, obviously, determined experimentally to account for non-uniformity of the fields, fringe effects, etc. The separation of hydrogen and deuterium ions would not pose the design problem because their energies differ factor two only. A TOF unit and a magnetic analyzer could be held at the ground potential whereas only the potential of the conversion plate should be changed. However, for such a magnetic field, the oxygen ions would pass magnetic analyzer with the energy of 1 keV only which is not sufficient for the TOF unit and additional ion acceleration is necessary. Therefore, it may be necessary to change potentials of the both conversion plate and all magnetic analyzer in order to have a possibility to study all species of interest by the same instrument. Another option is to have two (or even three) independent TOF units, one for oxygen ions (with the energy 16 keV, as in our case) and another for hydrogen and deuterium ions. The best scheme should be, as always, a trade-off, and would depend, obviously, on the resources (power, weight, volume) available for the instrument.

6.4 TOF analyzer

The principal scheme of the proposed TOF analyzer is shown in fig.10, which

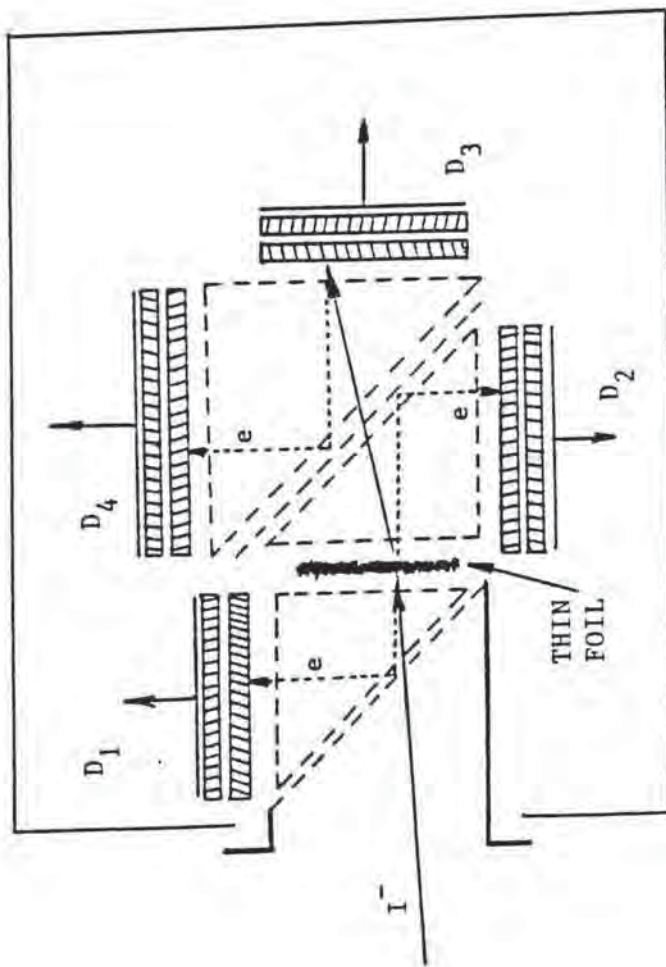


Fig.10 Principal scheme of TOF analyzer to identify and register negative ions I^- . Electrons emitted from thin foil are accelerated and directed by electrostatic mirrors to electron (START) detectors D_1 and D_2 . Particles are registered by (STOP) detectors D_3 (directly) and D_4 (by detecting secondary electrons emitted from the sensitive surface of D_3). Detectors are MCP chevron stacks. Front MCP of D_3 is covered by ion barrier film. Velocity of incoming ions is determined by the measurement of the time interval between START and STOP pulse.

represents a further development of the instrument for the study of energetic neutral atoms in space (*Gruntman and Morozov, 1982; Gruntman et al, 1990*). Negative ions bombard and penetrate a thin (40-100 Å) carbon foil. The incoming ions suffer some energy loss (which may result in emission of electrons) while penetrating the foil and proceed to the detector D_3 with reduced energy and a somewhat changed trajectory due to scattering. Electrons, emitted from the foil forward and/or backward, are accelerated, and after deflection by electrostatic mirrors, made from high transparent harp grids, are directed to detectors D_1 and D_2 respectively. All detectors $D_1 - D_4$ are identical microchannel plate (MCP) chevron stack detectors except detector D_3 , where front MCP is covered by a thin ion barrier film. When particle hits sensitive surface of the detector D_3 , it may trigger this detector and/or produce (backward) secondary electron, which would be accelerated and directed by an electrostatic mirror to the detector D_4 . Presented scheme contains new element: to my knowledge a MCP with an ion barrier film has never been used for particle detection and has never served to produce backward secondary electrons to trigger another detector. A somewhat similar scheme is often used with the solid state detectors for detection of particles of much higher energies (e.g. *Gloeckler, 1990*). The scheme contains two **START** detectors and two **STOP** detectors. This serves two goals: to make the scheme exceptionally redundant, i.e. in both channels, and to provide an opportunity to measure count rates of essentially noise-free triple and even quadruple coincidences.

Measurement of the time interval between the detection of an electron and detection of a particle by D_3 or D_4 gives the possibility to determine the velocity of negative ion. The width of the coincidence time gate and hence the noise coincidence count rate are proportional to the maximum possible time of flight of the neutral atom between the foil and detector D_3 . To minimize the noise, this flight distance has to be as small as possible. For a realistic diameter of sensitive area of TOF unit (e.g. thin foil) 1 cm, the flight length could be made 2 - 3 cm only. Typical times of flight of hydrogen and deuterium atoms in our example would be 15 ns and 30 ns correspondingly. The sensitive area of the detector D_3 should be somewhat larger than that of the thin foil in order to also collect particles which scatter substantially during penetration of the foil. The scattering will be much more pronounced for the detection of oxygen ions.

Several types of coincidences and TOF spectra are to be measured:

- i) The coincidence count rate from electron (**START**) detectors D_1 and D_2 (coincidence time gate for such coincidences may be very short, $\tau_e = 2 \text{ ns}$);
- ii) The coincidence count rate from particle (**STOP**) detectors D_3 and D_4 (coincidence time gate $\tau_p = 5 \text{ ns}$);
- iii) Nine TOF spectra (and nine different coincidence count rates respectively) corresponding to the possible combinations of three possible **START** signals and three possible **STOP** signals. The **START** signals : a) D_1 is triggered and D_2 is not triggered, i.e. $(D_1)\text{AND}(\text{NOT}(D_2))$; b) $(\text{NOT}(D_1))\text{AND}(D_2)$; c) $(D_1)\text{AND}(D_2)$. The **STOP** signals : $(D_3)\text{AND}(\text{NOT}(D_4))$; b) $(\text{NOT}(D_3))\text{AND}(D_4)$; c) $(D_3)\text{AND}(D_4)$.

The absolute values of the detectors' count rates are determined mostly by the stray photons and particles within the instrument. The use of triple and quadruple coincidences make the measurements essentially noise-free and allow (together with the magnetic analysis) assured ion detection and identification.

It is important to mention here that background photons more energetic than hydrogen Lyman-alpha (the most important line in the EUV background is 584 \AA) may produce simultaneous emission of two photoelectrons from different sides of the thin foil and create a $(D_1)\text{AND}(D_2)$ **START** signal and possibly tripple coincidence if another photon triggers D_3 simultaneously. The efficiency of such double photoelectron emissions is poorly known. However, if this efficiency is less than $2 \cdot 10^{-3}$, which is probably the case, then triple coincidences due to the helium resonance line at 584 \AA (which is approximately **100** times weaker than Lyman-alpha) would be less numerous than random tripple coincidences due to background photons.

For the energy of negative ions **8 - 16 keV**, the detection efficiency of the TOF unit would be rather high and, as a conservative estimate, the value $\epsilon_{\text{TOF}} = 0.1$ could be assumed for the detection efficiency of coincidences.

An axis of the TOF unit has to constitute some angle with the trajectory of the incoming negative ions. Negative ions entering TOF unit would be deflected during a passage of the reflecting gap of the first electrostatic mirror. The dependence of the deflection angle on the ratio of the voltage in the gap U_m to ion energy E_0 is presented

in fig.11. Initial angle of incidence on the reflecting gap is 45° . One can see that the effect is rather small and for realistic voltage in the gap, say **1000 V**, the deflection angle would not exceed few degrees.

6.5 Signal count rate

Let us assume that instrument sensitive area is 1 cm^2 , field of view is $15^\circ \times 15^\circ$, which allows to intercept all flux of deuterium or oxygen atoms and a substantial part of the flux of hydrogen atoms. If we assume that half of the negative ions of selected mass can pass magnetic analyzer as well as that, as we did earlier, the conversion efficiency to negative ions is **0.01**, and the detection efficiency by TOF unit is **0.1**, then the overall efficiency of instrument would be $5 \cdot 10^{-4}$.

This value of the detection efficiency would result in typical count rates of $I_H = 2.5 \text{ s}^{-1}$, $I_D = 1.5 \cdot 10^{-4} \text{ s}^{-1}$, and $I_O = 0.3 \text{ s}^{-1}$ for interstellar hydrogen, deuterium and oxygen atoms correspondingly. Let us assume that noise count rate of the detectors is as high as 10^2 s^{-1} . Then for coincidence (TOF) time gate of **50 ns**, one would get the random (noise) double coincidence count rate $5 \cdot 10^{-4} \text{ s}^{-1}$. For triple coincidences, random count rate would be less than 10^{-9} s^{-1} . One has to remember that this is a conservative estimate. However, even for such conditions, all three fluxes of atoms could be **reliably measured**. Even for the worst case of deuterium atoms, one could expect count rate as much as **15 count/day** without noise. Even a tiny fraction of negative hydrogen ions reaching somehow, say, by scattering from surfaces of construction elements within the instrument, may pose a danger to the measurements of deuterium atoms. However, one could expect that deuterium ions would be concentrated within a range of few nanoseconds on TOF spectrum whereas scattered hydrogen ions/atoms would have very broad energy distribution and correspondingly broad range of times of flight. The latter as well as the proper design of baffles and stray particle traps within the instrument should allow reliable detection of deuterium ions. Detection of the molecular hydrogen also would be possible and it would be possible to distinguish molecules from atoms as far as flux of molecules is comparable to hydrogen atom flux coming from the same direction of the observation.

The proposed instrument may also be used for registration of ENAs from heliospheric interface region. These particles could be separated from interstellar gas

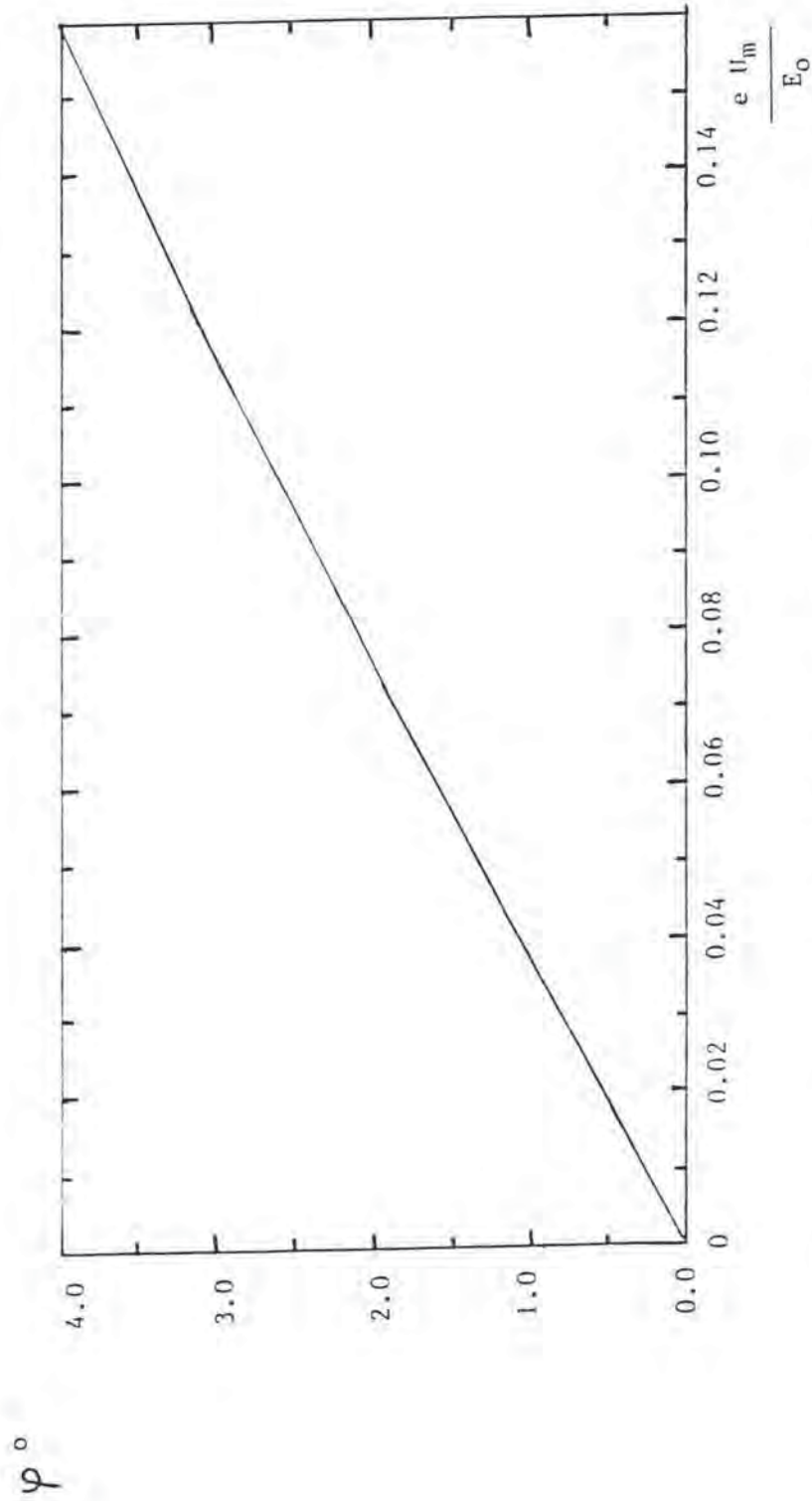


Fig.11 The dependence of the deflection angle of negative ions (with energy E_0) trajectory on voltage U_m in the reflecting gap of electrostatic mirror.

hydrogen atoms by the proper choice of accelerating voltage for negative ions before entrance to magnetic analyzer. Though only a fraction of negative ions would pass through magnetic analyzer due to substantial initial energy spread of ions, a conversion efficiency would be somewhat higher. One could expect that their count rate would be on the level of 10^{-2} s^{-1} .

7. CONCLUSION

Proposed new approach for *in situ* detection of neutral atoms in interplanetary space should be capable to register not only interstellar hydrogen atoms but also such minor constituents as deuterium and oxygen atoms as well as hydrogen molecules. It is important that experiment can be performed from a high apogee Earth-orbiting satellite. The technique uses a new approach - conversion of the atoms to negative ions which has been never utilized earlier in space instruments. At the moment, it is difficult to select proper conversion surface material, though pure barium seems to be promising. This question requires further extensive laboratory study as well as the conversion to ions of oxygen atoms.

Dynamic characteristics of the expected fluxes of interstellar atoms at the Earth's orbit and possibility to noise-free register and identify atoms should allow to determine unambiguously for the first time the composition (including minor, but very important, constituents) of interstellar gas in the LISM.

APPENDIX

Possibility to study planetary upper atmospheres and exospheres

Conversion of the atoms and molecules to negative ions may be used in a novel sensitive and efficient mass-spectrometer (similar to the described above) for the study of upper atmospheres and exospheres of planets at the heights where conventional mass-spectrometer technique does not have enough sensitivity. Besides hydrogen, its isotopes, and oxygen atoms, there are another atoms that present interest for the study of the environment of planets and the Moon, which can form negative ions and, hence, be detected by the proposed technique. These atoms are C (electron affinity 1.26 eV), F (3.40 eV), Si (

1.39 eV), P (0.75 eV), S (2.08 eV), and Cl (3.62 eV). Interesting possibility is to try to convert to negative ions such important for atmospheric chemistry molecules as OH (electron affinity 1.83 eV), Cl₂ (2.44 eV), ClO (2.0 eV) and O₃ (2.1 eV).

The conversion of low energy atoms with energies of a fraction of eV seems not to be studied so extensively as for higher energies (see e.g. *Seidl et al, 1989; Melnychuk et al, 1990*). The situation is even worse for molecules, which may dissociate at the impact on the surface. It should be noted here that absolutely no data are available on the conversion of molecules to negative ions at the surfaces. An adsorption of the relatively low energy atoms and molecules may also pose problem for the study of upper atmospheres and exospheres.

Earth

For the Earth, the velocity of a spacecraft at the low Earth orbit is 7 km/s and it corresponds to the energy of 0.25 eV/nucleon. The conversion process has energy threshold for cold conversion surfaces which is equal to the difference between work function of the surface and affinity energy of the atom. Conversion surfaces with as low work functions as 0.9 eV have been reported and work function of the order of 1 eV has been obtained for stable surfaces (*Souzis et al, 1989; Melnychuk and Seidl, 1991*). The heating of the converter would result in lowering of the effective energy threshold though conversion efficiency would also be low. It should be noted that even a relatively low conversion efficiencies, say 10⁻³ - 10⁻⁴, would provide higher sensitivity than conventional mass-spectrometers. It is still unclear whether it is possible to apply the technique for the detection of atomic hydrogen in terrestrial atmosphere and exosphere and this question requires a further detailed study. As far as heavier atoms are concerned, there is no doubt that they can be efficiently detected.

Moon

The orbital velocity around the Moon is 1.7 km/s, which corresponds to the energy of 0.014 eV/nucleon. This situation is much worse than that for the Earth as far as the detection of hydrogen atoms is concerned. The heavier atoms, such as oxygen and silicon, can be efficiently detected.

Giant planets

The proposed technique can definitely be used for the study of giant planets. For

example, an orbital velocity around the Jupiter corresponds to the energy of almost 10 eV/nucleon and atoms with such energy can be efficiently converted to negative ions.

ACKNOWLEDGEMENT

I wish to thank Professor Aart Kleyn, Dr. Roon Van Os, and Professor Milos Seidl for discussions of conversion on surfaces and for copies of publications they sent to me.

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