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POSSIBILITY OF EXPERIMENTAL STUDY OF ENERGETIC NEUTRAL ATOMS IN INTERPLANETARY SPACE

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Résumé

During last several years the interest to the potential opportunities of neutral atom direct study in interplanetary space increased significantly. The expected science return impo important for Solar system physics prompted the development of new techniques and instruments. This paper is devoted to the description of the coincidence technique developed for the direct detection of energetic neutral atoms in space and primarily of neutral Solar Wind. The concept of the technique was developed and the flight instrument was built. This instrument may provide unique scientific data. It is natural to extend the application of the described technique to the study of more heavy energetic neutral atoms. The origin of such fluxes is related to the important processes in planetary magnetospheres.

Among the most interesting objects, which may be studied by the technique, are neutral Solar Wind, energetic neutrals from terrestrial magnetosphere, particularly due to the ring current decay, energetic neutral emission from magnetospheres of Jupiter and Saturn and heliospheric boundary.

It is known now that the interplanetary space contains the fluxes of neutral atoms of different origin. Characteristics of these fluxes reflects physical processes in Solar system. Among the most interesting objects can be mentioned energetic neutrals from terrestrial magnetosphere, particularly due to the decay of the ring current, neutral Solar Wind, energetic neutral emission from magnetospheres of Jupiter and Saturn and heliospheric boundary.

During last several years the interest to the potential opportunities of neutral atom direct study increased significantly. The expected science return important for Solar system physics prompted the development of new techniques and instruments [1]. This paper is devoted to the description of the coincidence technique developped for the direct detection of energetic neutral atoms (ENA) in space.

1. Basic idea

To determine the number density of the neutral particles in space is not an easy task. The expected number density (e.g. $N \simeq 10^{-5} \div 10^{-3}$ cm^{-3} for neutral Solar Wind at 1 AU from the Sun) is low enough to prevent the use of the traditional technique based on the preliminary ionization of the neutrals by, say, electron impact with consecutive analysis of the ions produced. The ionization probability for neutrals does not generally exceed 10^{-4} resulting in a prohibitive signal to noise ratio since the noise count rate, inherent for the most convenient detector types, is in the range 10^{-2} - 10 s^{-1}. It is therefore crystally clear that such a low detection efficiency would result in a unacceptably long duration of the experiment, to say nothing about the detection of the possible transients.

The encouraging approach to the measurement problem is based on the fact that neutrals to be detected are of high energy and they can be studied by measuring their flux density instead of their number density.

Energetic neutral atoms impinging on a surface produce secondary electrons with a rather high efficiency. Therefore their flux density can be detected by counting the electrons by secondary electron multipliers, particularly of the microchannel plates (MCP) type. Unfortunately, the outer space is a extremely hostile environment for such detectors, since it is filled by extreme ultraviolet (EUV) photons. This diffuse background creates superiour flux of photons (predominantly Ly-alpha photons, $\lambda \approx 1216$ Å), which also may produce photoelectrons from the sensitive surface of the secondary electron multiplier. The expected EUV flux density is 4 to 5 orders of magnitude greater than that of the neutral Solar Wind [1], while photon detection efficiency may be as high as 0.1 [2]. The high photon background count rate prohibits the straightforward applic tion of such detectors in space experiments and was the main reason preventing experimentalists from direct neutral detecting in the interplanetary space earlier.

The ENAs may be ionized with rather high efficiency (up to 0.1) by stripping in the gas or plasma targets and in thin foils. Then the fast ions produced may be analyzed and detected by ion analyzer. This technique is standard in passive corpuscular diagnostics of fusion plasmas [3] . The use of the gas or plasma targets is prohibited for long duration space experiments by practical considerations. As the disadvantage of the method may be considered the use of the scanning technique or alternatively an array of a number of independent detectors to perform energy analysis of the ions produced. Such an analysis is of great importance since it may provide a valuable information on the ENA flux characteristics. Another important requirement for the detector is to function in unfavourable conditions with high background count rates due to stray EUV photons. This requirement is poorly met in the approach widely used in fusion plasma diagnostics. This fact prohobits the use of such approach to detect very weak ENA fluxes which are characteristic for the interplanetary space.

The vital problem of inherent weakness of ENA fluxes and gigantically superior EUV radiation background may be tackled by virtue of the coincidence technique. For the first time this approach was outlined in late seventies [4,5] to cope with the difficulties of experimental stydy of neutral Solar Wind and more generally ENA in space. Detailed analysis of such an approach and built prototype instruments were later described in [1,6] .

To achieve coincidence, the arrival of a neutral at the ENA detector must produce two independent detectable physical phenomena (e.g. electron emission), whereas only one occurs when a background photon arrives. The only events that signal particle arrival are those that occur when two independent phenomena are detected simultaneously, i.e. during a certain coincidence time interval τ_0 , which is the maximum time interval between two signals for which they can still be called coincident. Background coincidences (noise) arise from the detection of two photons that arrive during τ_0. Therefore, signal count rate $S \sim I_n$ and the nois one $N \sim I_\nu^2 \tau_0$, where I_n and I_ν are fluxes of neutrals and photons respectively. The signal to noise ratio is then $S/N = (I_n/I_\nu)/I_\nu \tau_0$. The ratio (I_n/I_ν) may be considered as independent of the instrument aperture for almost all practically interesting cases. Therefore $S/N = 1/(I_\nu \tau_0)$. Hence the signal to noise ratio may be increased by a decrease in the aperture (and consequently I_n and I_ν). This is the way the neutral atom flux registration may be performed in the presence of an essentially superior photon background.

It is interesting to underline that the noise suppression factor is a function of the absolute value of the flux to be detected. The lower is the flux, the greater is the noise suppression. Therefore, for any arbitrarily given original ratio of fluxes of neutrals to photons in space, an instrument aperture can be chosen which provides the required signal to noise ratio. One should also remember that the lower is the instrument aperture, the greater observation time is required to get statistically confident results. The requirements for signal to noise ratio and observation time (i.e. statistical accuracy) are contradictory and the trade-off, obviously, mist be found in every particular case.

2. Instrument. Prototype.

2.1. Principle of operation

Principal scheme of the time-of-flight (TOF) detector-energyanalyser (DEA) for ENAs is shown in fig.1. The DEA operates in essentially coincidence mode and uses TOF technique which is similar to that widely used in nuclear physics experiments with heavy ions and fragments

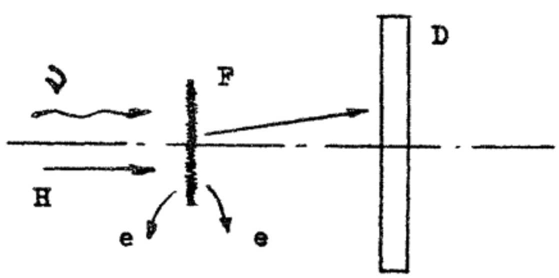

Fig.1. Energetic hydrogen atom detection by coincidence technique.

having energies of several MeV. Analogous technique was used for analysis of ions with the energy down to several dozens KeV [7]. We proposed to apply it to neutrals with energies lower by almost two orders of magnitude. The main constituent of neutral Solar Wind is expected to be hydrogen atoms. And the detection of such atoms by DEA is of the most interest.

The neutral particle penetrates the thin foil F causing the emission of electrons. After flying along a certain distance (flight length) with a somewhat reduced energy it reaches the particle detector D. The electron registration triggers the START signal for the TOF analyser (which measures the time interval and stores the result) and the heavy particle detection triggers the STOP signal. This technique permits the velocity (energy if the mass is known) of the particle to be determined, and is essentially a type of a coincidence method.

The photon would either be absorbed by the foil F (which may result in photoelectron emission practically indistinguishable from the electron emission due to the heavy particle penetration) or trigger the particle detector after passing unobstructed through the foil.

Only heavy particle may produce both secondary electron from the foil and triggering of the particle detector D in coincidence, i.e. within the time interval τ_0. The value τ_0 is determined by the longest possible flight time of the heavy particle between the foil and the particle detector D. For a fixed flight distance the flight time is a function of the minumum possible energy E_{min} of a particle after the foil. The minimum possible energy is determined from both the expected initial value of the energy of the neutrals to be detected and from the fact that the detection efficiency of particles by D drops abruptly down from the certain energy value. Therefore if one has particles with energy lower than this value, they will not be detected by D. By the rule of thumb, we accept for E_{min} the value of 100 eV. This energy determines the maximum value of the time interval, up to which the TOF analyzer should measure and memorize the time intervals.

2.2. Laboratory simulation

Three various prototype DEAs are built and tested under irradiation by monoenergetic hydrogen atom fluxes with energy in the range from 600 up to 3000 eV (as expected for the neutral Solar Wind) [5,6].

DEA type A is shown in fig.2-A. The carbon foil has a thickness of 80 Å and is supported by the fine mesh with 65 % geometrical transparency. Chevron stack of two MCPs is used to detect particles and electrons. No special attempts were made to match the anode to the 50-Ohm cable. The electrons accelerated by an input MCP voltage U_1 outrun the heavy particle and are registered by D. Only then does the heavy particle reach D where it may be registered. The DEA-A is based on the single channel mode (START and STOP are triggered by the same detector and are sent along the same line) of TOF analysis with a single detector.

DEA-B (fig.2-B) uses the additional funnelled channel electron multiplier to detect secondary electrons (START). DEA-B utilizes the two-channel mode of TOF analysis with two detectors.

DEA-C (fig.2-C) is based also on the two-channel mode of TOF analysis but with a single detector only. The detector's collector is divided into two parts. The shift of the MCP detector from the axis and the addition of an electrode E biased at U^* create an electrostatic field configuration such that electrons are registered primarily by the lower part of the collector (START) and heavy particles primarily by the upper part (STOP). To avoid the appearance of simultaneous signals in both lines arising from particles impinging on the central part of the first MCP, the shield S of 3 mm width is placed in front of D.

The flight distance in all types of DEA is approximately the same - 3 cm. The MCP stack sensitive area is 28 mm. The characteristics of all DEA types are similar and describ-

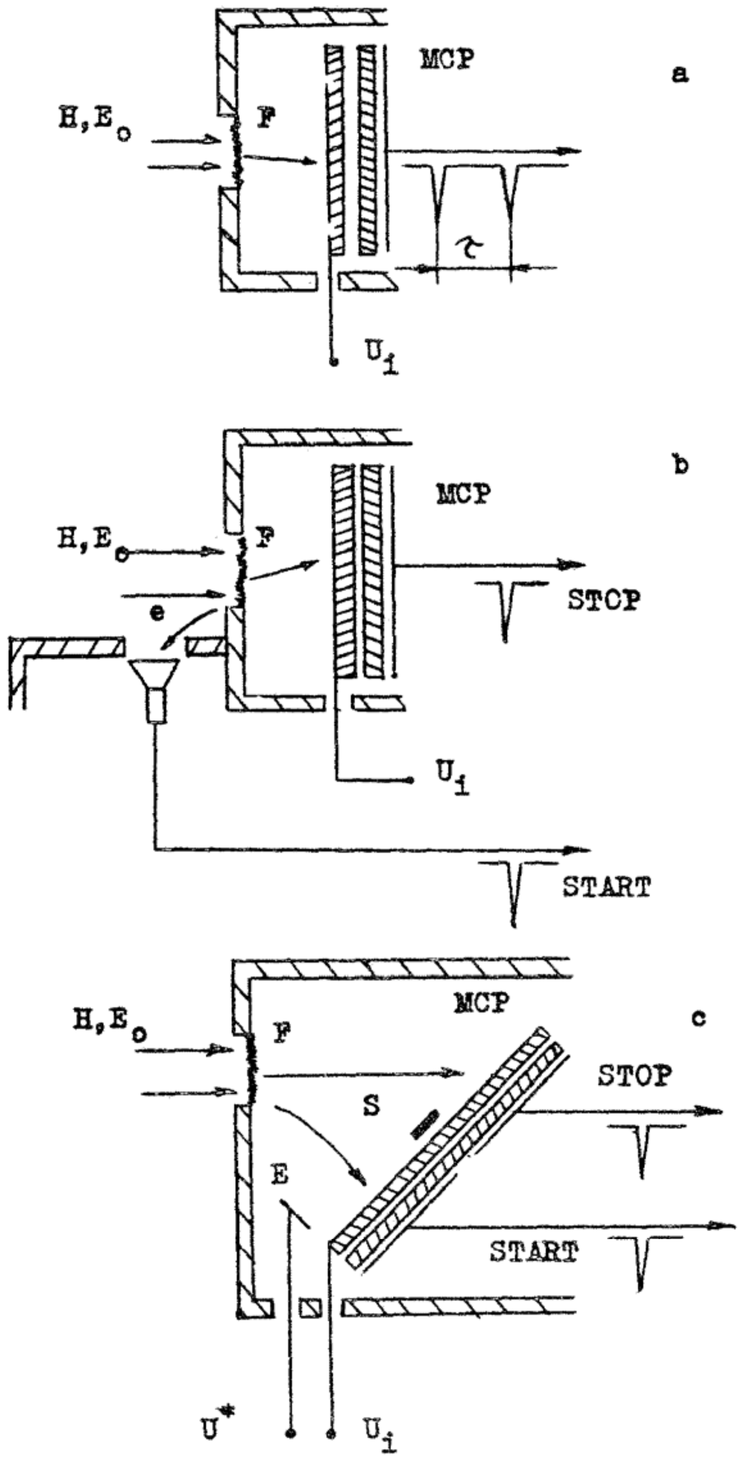

Fig.2. Time of flight detector-energyanalyzer.

a) one channel mode
b) two channel mode
c) two channel mode

ed in detail in [5,6] with the discussion of the advantages and disadvantages inherent to different schemes.

The typical TOF spectra for the detection of monoenergetic (E_0) hydrogen atom fluxes are shown in fig.3. The dependence of the detection efficiency on E_0 is presented in fig.4.

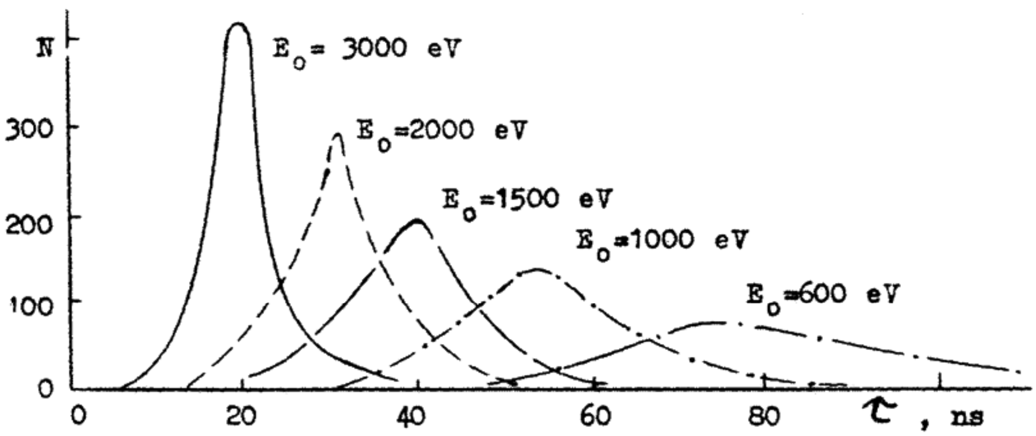

Fig.3. Typical time-of-flight spectra for the detection of monoenergetic (E_0) hydrogen atom fluxes.

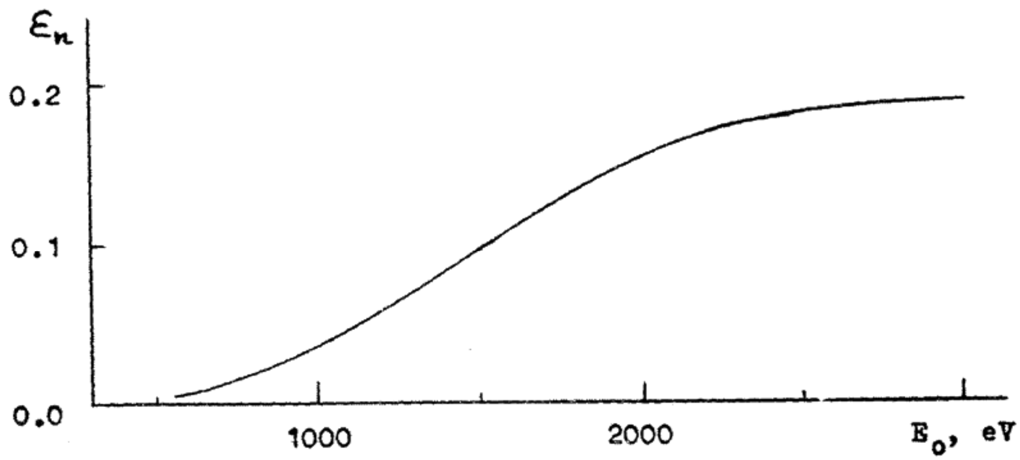

Fig.4. Dependence of hydrogen atom detection efficiency on E_0.

The laboratory study of the performance of the DEA prototypes may be summarized as follows: they provide detection of hydrogen atoms of 600-3000 eV with an efficiency 1-20 % and an energy resolution E/ΔE of about 2. The detection is realized in the coincidence mode that ensures the extraction of the weak neutral atom signal from the superior EUV background.

For hydrogen atoms with 1 keV energy typical for the neutral Solar Wind the detection efficiency is ≈ 3 %. The poor energy resolution is determined by the straggling: energy loss during penetration through the foil is a statistical process. The angular scattering in the foil also deteriorates to some extent the energy resolution. With the increase of the particle energy, the relative effect of both straggling and scattering diminishes and the energy resolution improves.

For the particle energy range of interest, the TOF spectra are not influenced by the electrostatic field between the foil and the detector, since only few per cent of hydrogen atoms emerge from the foil in charged state. Only with the energy increase over 10 keV, the charged constituent among the emerging particles becomes significant and should be then taken into consideration.

As can be seen from fig.3, the widths of the TOF spectra are not less than 10 ns. This fact implies very modest requirements to timing electronics: simple leading edge discriminators may be used; walk, drift and jitter problems may be neglected; the number of channels to memorize time intervals distribution may not exceed several dozens; etc.

2.3. Calibration

A comment should be made on the calibration, i.e. determination of the absolute detection efficiency of the instrument. This is usually the head-ache problem. The coincidence mode realized in the instrument gives a unique opportunity to measure absolute intensities of neutral particle fluxes without detector calibration, provided that there is no background. The particle arrival at the detector may result in two independent events: (1) emission of the electrons from the foil and their detection and (2) heavy particle registration by D. Let I_0 be the intensity of the flux to be measured and P_1 and P_2 be the probabilities, which are unknown a priori, of registering events (1) and (2). Then $I_1 = I_0 P_1$, $I_2 = I_0 P_2$ and $I_c = I_0 P_1 P_2$, where I_1 and I_2 are respectively count rates of events (1) and (2), which can be measured, and I_c is the measured coincidence count rate of events (1) and (2). Hence, the value I_0 may be derived from measured quantities as $I_0 = (I_1 I_2)/I_c$, and P_1 and P_2 (and detection efficiency $\varepsilon_n = P_1 P_2$) may be derived from these measurements likewise. One can see, no preliminary calibration is necessary.

2.4. Signal to noise ratio

Let us consider the instrument performance under simultaneous neutral particle and photon fluxes illumination. Let the instrument sensitive area and field of view (FOV) solid angle be S_d and Ω_d.

The noise coincidence count rate due to photon flux is

$$R_\nu = \varepsilon_\nu \varkappa_\nu \gamma_e \varepsilon_e \tau_0 F_\nu^2 S_d^2 \Omega_d^2$$

where ε_ν - detection efficiency of photons by D; $\varkappa_\nu$ - foil transmission for photons; γ_e - photoelectron emission efficiecy from the foil; ε_e - detection efficiency of electrons; τ_0 - coincidence time interval; F_ν - EUV photon flux number density (per unit solid angle).

The signal coincidence count rate due to flux of neutrals is

$$R_n = \varepsilon_n F_n S_d \Omega_d$$

where ε_n - detection efficiency of neutrals by the instrument; F_n - flux number density (per unit solid angle).

For Ly-α photons $\varepsilon_\nu = 0.03$ [8,9] ; $\varkappa_\nu = 1.2\ 10^{-1}$ and $\gamma_e = 1.2\ 10^{-3}$ [10] ; let $\varepsilon_e = 0.8$ [11] , $\varepsilon_n = 0.03$ and $\tau_0 = 100$ ns.

The signal to noise ratio is then

$$\Delta = \frac{R_n}{R_\nu} = \frac{\varepsilon_n F_n}{\varepsilon_\nu \varkappa_\nu \gamma_e \varepsilon_e \tau_0 F_\nu^2 S_d \Omega_d} \approx 10^{11} \frac{F_n}{F_\nu^2 S_d \Omega_d}$$

The flux of EUV photons (predominantly in Ly-α) is due to the radiation of the Solar corona and the resonant scattering of the Solar light by the interstellar gas inside the Solar system. If the instrument is directed along a line which is off-set by more than 2° from the Sun (for neutral Solar Wind measurement experiment the off-set angle equals 4 - 6°), the photons scattered by the interstellar gas become the prime constituent of the background EUV radiation, providing the baffle system is ideal. Then, $F_\nu \leq 600$ Ra [12], i.e. maximum $F_\nu = 5\ 10^7$ ph sm^{-2} s^{-1} sr^{-1}. Let be $S_d = 3$ cm^2 and $\Omega_d = 5°*5° \approx 10^{-2}$ sr. Then, for the minimum expected value $F_n = 10^4$ cm^{-2} s^{-1} sr^{-1}

$$\Delta = 10$$

and $R_n = 10$ s^{-1}.

It should be noted that these estimates for Δ and R_n values are on the conservative side and it is rather probable that Δ and R_n would be one order of magnitude greater.

3. Flight instrument concept

The experience gained with the prototypes of the TOF detector-energyanalyzer is the foundation for the concept of a modified version wich might be designed for the on-board operation. The general scheme is shown in fig.5. The instrument consists of a light baffle, filter (optional) and detecting assembly; estimated weight - 5 kg, power consumption - 3.5 Wt.

Baffle. The light baffle is approximately 60 cm long with the outlet orifice diameter equal 27 mm; its FOV solid angle has 4-5° diameter. There is a permanent magnet inside the baffle deflecting entering ions (up to 50 keV for protons) and electrons. Since the instrument is to be pointed along the direction with a 5° off-set angle from the Sun, which is an extremely bright EUV source ($4\ 10^{11}$ cm^{-2} s^{-1} at Earth orbit [13]), the quality of the baffle is the crucial factor. Two possibilities are considered: 1) the baffle must be of the highest possible quality, if no special filter is used; 2) the baffle may be as simple as possible (with corresponding poorer performance) if the filter is installed.

Filter. We propose to install at the immediate entrance of the detecting assembly a specially designed filter - the nuclear track filter (NTF) or molecular sieve, as it is also called, - to suppress EUV photon flux and to increase the ratio of neutrals to photons. The advantage to use NTFs for this purpose was for the first time emphasized by us in [1]. At the same time, independently, NTFs were proposed to use as filters in EUV and soft X-ray astronomy [14].

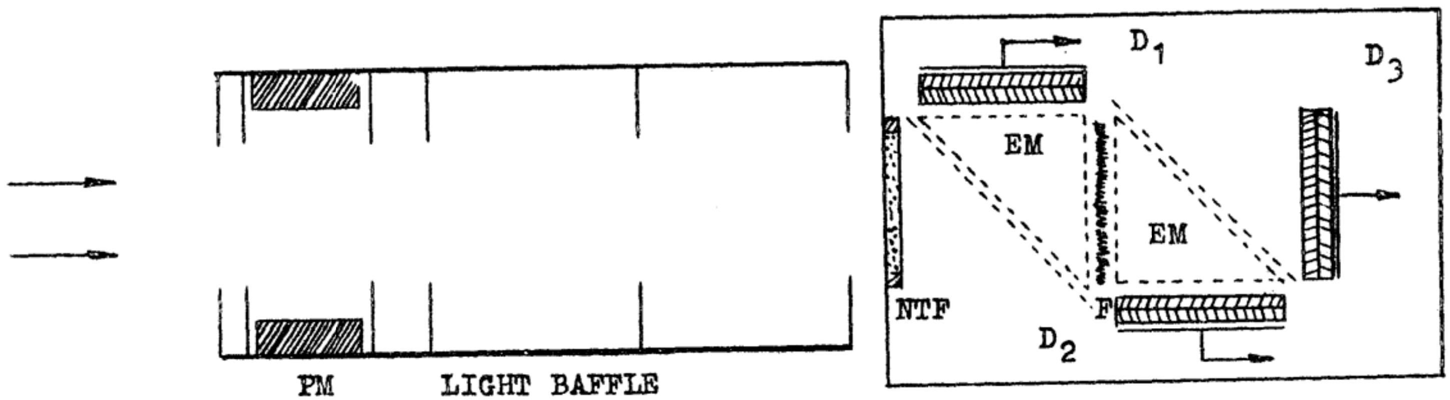

Fig.5. Neutral solar wind detector-energyanalyzer. D_1, D_2 and D_3 - MCP detectors, PM - permanent magnet, EM - electrostatic mirror, F - foil, NTF - nuclear track filter.

Several reviews (e.g. [15,16]) were devoted to NTF technology and characteristics. The thin (1-100 μm) organic foils (say, Macrofoil® [17]) or mica are bombarded by heavy (e.g. Xe^{+}) ions with energies of several MeV per nucleon. The pores (cylindrical or conical) are etched afterwards in the foil along the ion tracks. The etched straight channels are transparent for neutral particles but their transparency for the photons is a strong function of the wavelength.

Now, the following NTF parameters seem to be necessary:

- working area diameter 27 mm;
- foil thickness - 1 μm;
- channel diameter - 1000 Å;
- channel length to diameter ratio - 10 (therefore the instrument FOV is not obstructed by NTF);
- geometrical transparency $\geqslant$ 10 %.

Though only 10^{-1} of the original flux of neutrals would pass through such structure, the preliminary estimates show that only 10^{-8} of the Ly-α (1216 Å) flux and 10^{-4} of the 584 Å photon flux would pass through it. Thus Δ may be substantially increased.

The NTFs with such parameters never have been produced or used before, though there seems to be no unsurpassable technological difficulties. The long time degradation under EUV illumination, the effects due to short time hit by direct unobstructed Solar light, the sink of the absorbed energy and other features are virtually unknown. That is why the filter is considered to be optional, and experiments now under the way should resolve the problem.

The NTFs would extremely improve the ability of the instrument to extract the neutrals from the EUV background. Their application may permit even to detect energetic neutral hydrogen atoms, emitted from the Solar Wind termination region.

Detecting assembly. All detectors D_1, D_2 and D_3 (fig.5) are commercially available chevron MCP stacks with the sensitive area of 27 mm diameter. The 80 Å carbon foil supported by the fine mesh has also a 27 mm diameter. The flight distance between foil and D_3 is 6 cm. Two identical detectors D_1 and D_2 are used to detect electrons emitted from the foil. Two electrostatic mirrors constructed from the 95 % transparent harp grids provide isochroncus transport of emitted (and accelerated up to 1000 eV) electrons to corresponding detectors.

Electronics unit. The electronics unit includes three identical chains of amplifiers and discriminators, four counters, time-to-digital converters (TDC), three 32 channel memories, high voltage power supply. High voltages supplied for detectors and exposure time are preset by digital command. The emergency voltage drop is forseen under certain conditions. Three counters accumulate counts of the three detectors D and one counter accumulates coincidence counts (coincidence time interval 10 ns) of D_1 and D_2. Three TOF spectra (with unequal channel widths) are accumulated varying in the three different types (sources) of START signal (the STOP signal is provided by D_3):

1. START signal is provided if only D_1 (and not D_2) is triggered;
2. START signal is provided if only D_2 (and not D_1) is triggered;

3. START signal is provided if D_1 and D_2 are triggered simultaneously.

Such instrument concept provides the necessary redundancy (the falure of either D_1 or D_2 is not "mortal" for the experiment) and house-keeping information. The third type TOF spectrum is accumulated under substantially better signal to noise ratio condition (but reduced detection efficiency) which may provide important information for treating the data. Moreover, this third spectrum may become extremely important if atoms heavier than hydrogen or helium are detected, being the case for the emission of neutrals from Jupiter and/or Saturn magnetospheres. For example, 5 keV energy sulfur atom hardly would be able to penetrate through the foil and hit D_3, but it seems to be able to produce secondary electrons from both sides of the foil with high efficiency.

The first two time channels in the each TOF spectrum correspond to the events when D_3 is triggered first and then are triggered D_1 and/or D_2. Therefore these channels provide simultaneous measurement of the level of random (noise) coincidence count rates. The next two channels in each spectrum correspond to very high velocity and provide information on high energy particles (undeflected protons, α-particles....).

The additional electronics unit is to be used to interface described instrument to the particular spacecraft telemetry system.

5. Conclusion

To study neutral Solar Wind (and energetic neutral hydrogen fluxes of another origin), the concept of the technique was developped and the flight instrument was built. This instrument may provide unique scientific data important for Solar system physics.

It is natural to extend the application of the described technique to the study of the fluxes of more heavy energetic neutral atoms (He, O. S). The origin of such fluxes is related to the important processes in terrestrial magnetosphere and that of Jupiter and Saturn. However for this application, some new ideas are to be introduced and the instrument is to be modified. Such a work is now in progress in the lab.

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