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A miniaturized fission ionization chamber for Near-Sun missions to search for a quasi-steady flux of > 1 MeV solar neutrons

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Abstract. We report on an initial development effort for a prototype of a small yet sensitive neutron detector targeted toward a search for a possible quasi-steady flux of fast (> 1 MeV) solar neutrons. The detector is suitable for inclusion on missions going inward from the Earth toward the Sun, such as the ESA Solar Orbiter or the Bepi-Colombo Mercury Orbiter. Our goal has been to develop a compact, high sensitivity detector with the capability of performing a 10measurement of a flux of 1 n cm^{-2} s^{-1} in 24 hours for a mass less than 1.5 Kg and power consumption less than 2 W. Results from our work so far demonstrate the feasibility of such an instrument using a compact fission ionization chamber as the neutron detector.

1 Introduction

While it is well known that fast neutrons can be produced in large solar energetic particle (SEP) events, little is known about the flux of neutrons, if any, from the quiet sun. Discovery of a quasi-steady fast neutron flux would imply the near-continuous presence of energetic nucleons with energies of a few MeV at the Sun, providing important new information about energetic processes in the lower solar atmosphere. Searches for a low-level solar neutron flux at Earth are hampered not only by the $1/r^2$ fall-off in flux with radius, but also by the short half-life of neutrons, which results in most neutrons with energies of less than a few MeV decaying before they reach 1 AU. Fig. 1(A,B) illustrates the increase in intensity of neutrons with decreasing radius from the sun as a result of these combined effects. As was pointed out long ago by Simpson (1978), and as is clear from this figure, in searching for a low-energy low-intensity quasi-steady flux of solar neutrons there is an enormous advantage to be gained by going inwards from Earth's orbit. However, for an instrument to be suitable for inclusion an interplanetary mission that reaches heliocentric radii much less than 1 AU, it must be small, light, and consume little power. By contrast, most neutron detectors that have been flown or that are in development, based most commonly on detection of proton recoils from neutron scattering or moderation of neutrons for nuclear capture, have had masses of the order of several kilograms. Thus a new type of instrument is required.

Our instrument concept is based upon detection of neutron-induced fission from foils of fissionable material (e.g. Thorium or Uranium) in a compact pulse ionization chamber. For sensitivity we have chosen as a target the capability of performing a measurement of a flux of 1 n/(cm^2 s) with 10% accuracy in 24 hours. Such sensitivity should allow a sensitive search for a quasi-steady long-term flux and also provide information about neutron fluxes associated with discrete SEP events. With our prototype chamber we have demonstrated clean detection of neutrons with sensitivity consistent with our target in a sensor that, together with its electronics and housing, we expect will meet our mass and power targets, making it feasible for inclusion on modest-scale interplanetary space- craft.

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2 Scientific Justification

Neutrons provide one of the clearest available windows on acceleration and confinement of energetic nuclei in the solar atmosphere. Energetic nuclei in the solar atmosphere inevitably produce a flux of neutrons through interactions with ambient nuclei (e.g. Murphy et al., 1987). Thus neutrons produced in the solar atmosphere provide a direct indication of the density of energetic nuclei in the photosphere, chromosphere, and lower corona. There are indications of storage of energetic particles in the lower corona for periods of at least hours following major solar flare events (Kanbach et al., 1993). Energetic nuclei from the much more frequent smaller events, ranging down to the nearly continuous nanoflares (Parker, 1988) may also remain trapped near the sun by the strong magnetic fields near the active regions that are

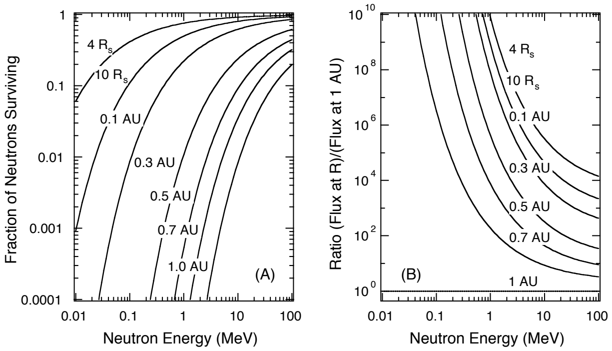

Fig. 1. A) Fraction of solar neutrons which survive to reach various radii vs. neutron energy; B) Flux enhancement at radius R over flux at 1 AU.

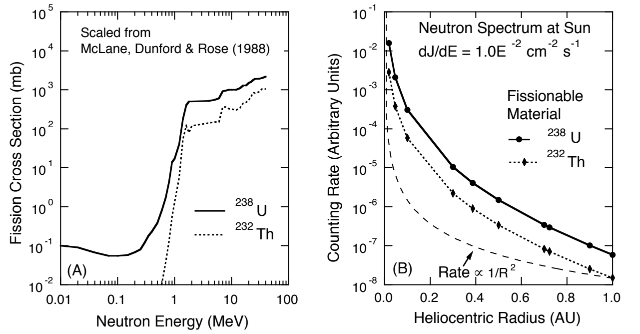

Fig. 2. A) Neutron-inducedfission-cross sections for ^{238}U and ^{232}Th; B) Expected counting rate vs. R for a power law solar neutron spectrum with an index of -2.

the most likely sites for their acceleration. New models of the nature of the coronal magnetic field, which appears to rotate rigidly with the sun, require continuous reconnection at the interface between the coronal and photospheric field to accommodate to the differential rotation of the photosphere (e.g. Wang and Sheeley, 1993; Fisk et al., 1999). This raises the possibility of quasi-continuous particle acceleration at the reconnection sites. Many of these energetic particles may never escape into the interplanetary medium where they could be observed. Such processes may very well result in the production of a quasi-steady flux of neutrons that would be undetectable from Earth.

3 Experimental Approach

Our chosen technique, detection of fission fragments from neutron-induced fission of heavy nuclei, lends itself to compact design and simplicity of operation. Fission detectors have previously been used in space on the Pioneer 10 and 11 missions to attempt to isolate nucleons trapped in Jupiter's magnetic field from an expected (and observed) overwhelming background of trapped electrons (Simpson et al., 1974). Fission fragments produce large signals in a charged particle detector that are easily distinguishable from the most common backgrounds from energetic charged particles such as trapped radiation in magnetospheres or cosmic radiation and SEP's. Use of a gas ionization chamber, as we propose, provides additional protection against such backgrounds since fission fragments have comparatively low velocities and ionize heavily in the gas, whereas most higher energy cosmic rays produce much less ionization in the gas. In a small chamber, only narrow energy ranges for heavy nuclei can produce signals in the gas comparable to those produced by fission fragments. Nevertheless, to search for the low fluxes that are our target, and to provide definitive identification of neutrons, an anti-coincidence shield surrounding the detector will be required. To minimize the weight of such a shield, small size for the detector is of paramount importance.

Our detector is designed to provide integral flux measurements of neutrons above an energy threshold set by the minimum energy required to induce fission in a heavy nucleus. As shown in Fig. 1A, even as close as 4 solar radii (Rs) to the sun, more than 50% of neutrons with energies less than ~100 KeV will have decayed before reaching the spacecraft. Therefore, a search for very low energy, thermal or even epithermal, neutrons is not likely to be successful. Our objective is to detect fast neutrons that can survive in significant numbers to reach the point of observation. For a solar probe or Mercury orbiter mission, Fig. 1A suggests that thresholds in the range of 1-10 MeV are appropriate.

As shown in Fig. 2A, our chosen material, ^{232}Th, provides a clean threshold for fission at an energy slightly above 1 MeV. A suitable alternative material would be Uranium, which has a larger fission cross-section, but is also susceptible to fission from lower energy and thermal neutrons and so provides a less clean threshold.

The counting rate in the detectors would be determined by the number of neutrons above the threshold that survive to reach the instrument. Fig. 2B shows the growth in counting rate with decreasing radius that would be expected for a chamber using Thorium and Uranium foils. Since the deviation in growth of the intensity from a $1/r^2$ law is a result of the energy-dependent survival of the neutrons, if there is a quasi-steady flux from the sun, the rate of intensity increase would offer some information concerning the neutron spectrum.

In a modest program over the past three years we have constructed and tested a laboratory model fission ionization chamber with the essential characteristics of the detector we would propose for flight. A schematic diagram of our chamber is shown in Fig. 3, and a photograph of the internal structure of the chamber as built is shown in Fig. 4. From addition of component masses, the total mass of the chamber (not yet including an anticoincidence and exclusive of the large gas filling tubes and valves which are appropriate only for a laboratory model) is approximately 375 gm. Little effort was expended towards minimizing the mass, especially in the base plate design, and we anticipate that significant reductions are possible.

To meet our target sensitivity, simple calculations suggest that using ^{232}Th foils, an exposed area of approximately 700 cm^2 is required. Our chamber was designed to hold 11 foils

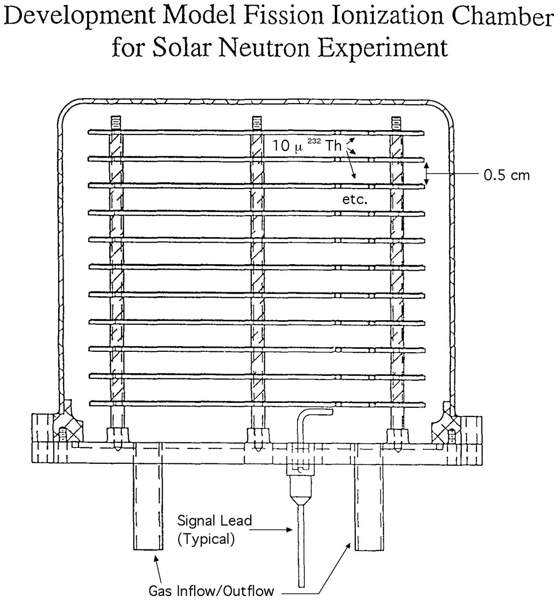

Fig. 3. Schematic of development model Fission Ionization chamber.

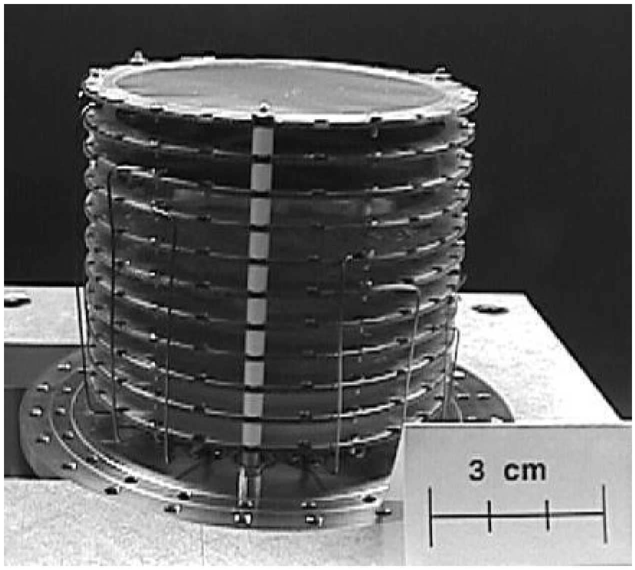

Fig. 4. Internal structure of Fission Ionization chamber as built.

with, when mounted, an exposed diameter of 6.4 cm. Fission fragments have a very short penetration range in matter. Therefore each side of a foil acts as an independent source of fission fragments. The foils themselves act as electrodes in the ion chamber and define the sensitive volume of the gas. With 11 foils, therefore, 20 sides are exposed to the sensitive volume for a total area of approximately 640 cm^2.

A foil thickness of 10 microns was chosen based upon runs with a Monte Carlo simulation program developed as part of this project. The results show that fission fragments produced more than 5 microns from the surface of a foil generally do not escape the foil and thus make no contribution to the neutron detection efficiency of the chamber. Therefore foils thicker than 10 microns provide no advantage. On the other hand, alpha particles from radioactive decay of atoms in the center of thicker foils continue to escape, contributing to background in the chamber. Alpha particle background is significant, and based on alpha decay of ^{232}Th and its daughter products, we expect that in a chamber fully populated with ^{232}Th foils, of order 10^5 alpha decays per second will take place. This raises concern about a possible background from multiple pile-up of alpha particle pulses that could simulate the comparatively rare fission events, and may require use of faster electronics than the micro-second scale electronics used for our tests.

Our test chamber incorporates four foils of ^{232}Th and one foil of natural Uranium provided at no cost as part of a cooperative effort with the Argonne National Laboratory. While it proved easily possible to produce 10 micron foils of Thorium, it was found that, probably due to work hardening in the rolling process, it was not possible to produce Uranium foils with thickness less than 40 microns. This provides further weight to our choice of Thorium as the foil material. However in the test chamber the Uranium was useful in providing a steady, if low, source of spontaneous fission events. The rest of the chamber was filled out with Aluminum foils, arranged to provide for separate measurements of fissions from the Th and U foils. (In flight, we anticipate that only one signal, representing the summed signal from all of the foils, will be brought out of the chamber. For the test chamber signals were brought out from each individual foil.)

The gas used in the chamber is 95% Argon/5% CO_2, selected because of concerns for degradation of gas mixtures containing methane under continuous radiation exposure. The chamber operates at a pressure of 1 atmosphere, but has been tested to a level of 100 psi overpressure. In this test configuration the chamber is operated at a bias voltage of 180 V.

4 Response of the Chamber

Figure 5 shows the response of the chamber to fission events produced in the ^{232}Th foils by neutrons from a Pu-Be source (provided by the Physics Department Instructional Laboratories at the University of Chicago). The source provides neutrons with energies up to ˜10 MeV. The large number of counts at low energy is produced by the radioactive decay alpha particle background in the chamber. In the absence of the neutron source, essentially no events are observed above a signal energy of about 8 MeV. The contribution from fission events when the chamber is exposed to the neutron source is clear. While the characteristics of the source are not well known , based on best estimates of its strength and of the beam geometry, the observed event rate would scale up to a detection efficiency of about 0.0015 fissions/(n/cm^2) in a chamber populated with 11 foils fully exposed to the neutron flux. This is consistent with our stated goal of being able to perform a measurement to 10% accuracy of a flux of 1 n/(cm^2 s) within one day.

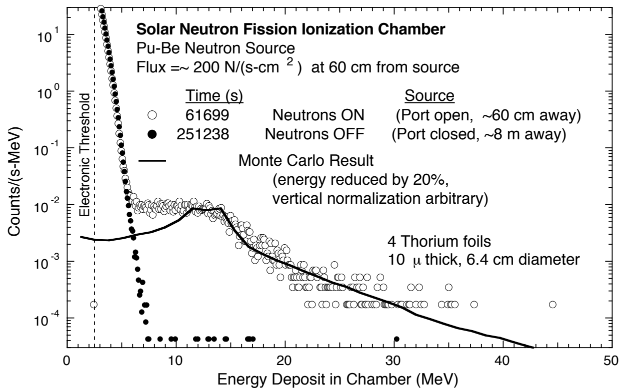

Fig. 5. Response of the chamber to neutrons from a Pu-Be source.

Superposed on the data in Fig. 5 are the results of a somewhat simplified Monte Carlo simulation of the response of the chamber to nuclear fission events. The simulation takes into account random depth of production of fission fragments in the foil, random orientation of the fission product paths, the energy loss characteristics of the very low velocity fission fragments, and the peculiar characteristics of pulse ion chamber response, where, because of the very low mobility of positive ions compared to electrons, the signal produced by collection of electrons depends upon where in the gap energy is deposited to create the electron/ion pairs. The major simplification is that rather than using a distribution of isotopes and energies for the fission fragments, all fission events are considered to produce the same light and heavy fragments consisting of single neutron rich isotopes of Kr and Xe at single representative initial energies. The energy deposits from the Monte Carlo simulation must be reduced by ˜20% to achieve a reasonable match to the data. The energy discrepancy is most likely a result of less than full charge collection in the chamber. Part of the deficit arises because, at our test operating voltage of 180 V, direct measurements of signal size vs. voltage from the alpha particle background show that we are still somewhat below the plateau in charge collection efficiency as a function of applied voltage. This effect is of order 5%. Also, even though the measurements were conducted with gas flowing through the chamber, we subsequently discovered a leak in the chamber that may have allowed some contamination of the gas. Later tests using signals from the alpha particle background suggest that this effect may have accounted for a 10-15% loss of signal. Therefore the two effects seem close to sufficient to account for the discrepancy.

After adjustment of the Monte Carlo result to compensate for these problems, the overall agreement in shape is reasonably good given the simplifications of the model, and the response clearly demonstrates the suitability of the technique for detection of low level neutron fluxes.

5 Present Status and Plans

The chamber continues to be operational in our laboratory, and a test of the long-term viability of the gas in the chamber as constructed is under way. While care has been taken to exclude materials that could contaminate the gas, contamination of the gas is a major concern for ion chambers, and clear demonstration of long-term operability without replenishment is required. However previous flight experience with a large sealed ionization chamber on the HEAO-3 spacecraft (Binns et al., 1981) shows that long-term operation of a sealed ion chamber is possible.

A proposal is being prepared for support for further development leading to a chamber closer to a flight prototype, including an anti-coincidence and flight-style electronics and incorporating lessons learned in construction of this first chamber. If successful, our intention is to search for a test flight as a piggy-back payload on a balloon mission, since conditions near the top of the atmosphere provide a flux of secondary neutrons similar to our target minimum detectable flux, as well as cosmic ray backgrounds very close to those in space.

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