

## SONTRAC: A Solar Neutron Track Chamber Detector

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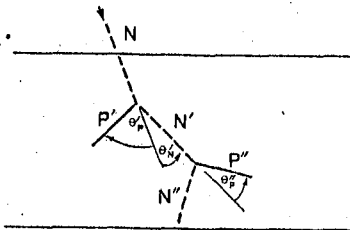
**1. Introduction.** The recent detection on the SMM satellite of high energy neutrons emitted during large solar flares (1) has provided renewed incentive to design a neutron detector which has the sensitivity, energy resolution, and time resolution to measure the neutron time and energy spectra with sufficient precision to improve our understanding of the basic flare processes. Over the past two decades a variety of neutron detectors has been flown on satellites and high altitude balloons to measure the atmospheric neutron intensity above 10 MeV and to search for solar neutrons. Most of these detectors have relied on n-p scattering as the basic detection process. In this paper we describe the SONTRAC (Solar Neutron Track Chamber) detector, a new type of neutron detector which utilizes n-p scattering and has a sensitivity 1-3 orders of magnitude greater than previous instruments in the 20-200 MeV range. The energy resolution is 1% for neutron kinetic energy,  $T_n > 50$  MeV. When used with a coded aperture mask at 50 m (as would be possible on the space station) an angular resolution of  $\sim 4$  arc sec could be achieved, thereby locating the sites of high energy nuclear interactions with an angular precision comparable to the existing x-ray experiments on SMM.

The scintillation chamber has been investigated as a track chamber for high energy physics, either by using arrays of scintillating optical fibers or by optical imaging of particle trajectories in a block of scintillator. Recently square plastic scintillation fibers 0.2 and 0.1 mm in size have been developed (2), which makes it possible to construct a block of plastic scintillator composed of alternate layers of x and y oriented fibers in which the range and direction of proton recoils from n-p scattering can be determined with a spatial resolution of approximately 0.1 mm. The  $4\pi$  geometry and high spatial resolution make possible the enhanced detection efficiency and energy resolution over existing techniques.

## 2. Detection Efficiency and Energy Resolution.

Neutrons interact in plastic scintillator either by elastically scattering from hydrogen or by interacting with carbon (n-C). The n-p events (Fig. 1) are the most useful. If the source is a point source and its direction is known, measurement of the energy and direction of the recoil proton in a single scattering is sufficient to determine the incident neutron energy. For a double scattering event where the energies and directions of both recoil protons are measured, the energy and direction of the incident neutron are uniquely determined. Thus double scattering events can be used to measure the neutron intensity from an extended source such as the secondary neutrons produced in the atmosphere

N-P KINEMATICS



SINGLE SCATTER:

$$T_N = T_P' / \cos^2 \theta_p' = T_P' / \sin^2 \theta_N'$$

$$\theta_p' + \theta_N' = \pi/2$$

DOUBLE SCATTER:

$$T_N = T_P'' / \cos^2 \theta_p''$$

$$T_N = T_P' + T_N'$$

$$\vec{P}_N = \vec{P}_P' + \vec{P}_N'$$

Fig. 1. The kinematics for n-p scattering.

by the primary cosmic radiation. When a localized source such as the Sun is observed, the background is greatly reduced by restricting the accepted events to a cone about the solar direction. The interpretation of single and double tracks in plastic scintillator is complicated by (n,p) and (n,d) reactions in carbon. Fig. 2 shows the effective cross sections for  $^{12}\text{C}(n,p) +$

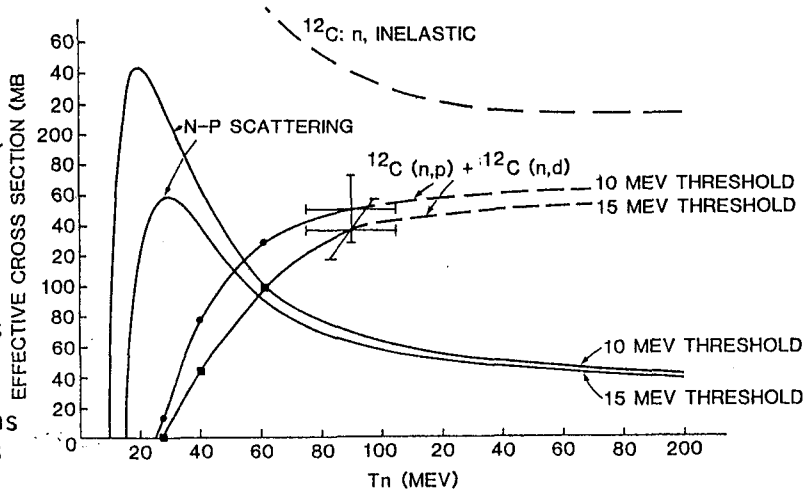


Fig. 2. Effective cross sections for (hydrogen and carbon).

$^{12}\text{C}(n,d)$  for proton kinetic energies  $T > 10$  and 15 MeV. Above 90 MeV the inelastic carbon cross section is an upper bound. The effective n-p scattering cross sections for the same threshold were calculated using the angular distribution parameterization of Rindi et al (3). Below 50 MeV n-p scattering predominates and single scattering can be used. Above 50 MeV, where the sum of the effective carbon cross section is larger than the effective n-p cross section, the kinematic criterion that  $\Theta_p' + \Theta_n' = 90^\circ$  identifies the double scattering events in which the first proton is from an n-p scatter. Above about 200 MeV most of the interactions will result in the emission of several particles from carbon which can be used to infer the neutron energy. SONTRAC's performance therefore is characterized by three interaction modes. The energy ranges over which these modes are applicable overlap, thereby providing a check of internal consistency.

**A. Single Scattering Mode.** The detection efficiency in the single scattering mode is shown in Fig. 3 for an infinite slab of CH of various thicknesses where the neutron direction is normal to the slab and the

proton track stops within the slab. The curves reflect the initial rise above the threshold energy, the decrease in the n-p cross section with energy, and an increase in slope above 100 MeV as tracks are increasingly lost out the bottom. The corrections for loss of tracks out the sides of a finite size detector are small. For a cube 60 cm on a side, the efficiency is reduced by 2.7% at 100 MeV and 9.5% at 200 MeV. The high efficiency in the 15-40 MeV region where n-C contamination is low makes the single

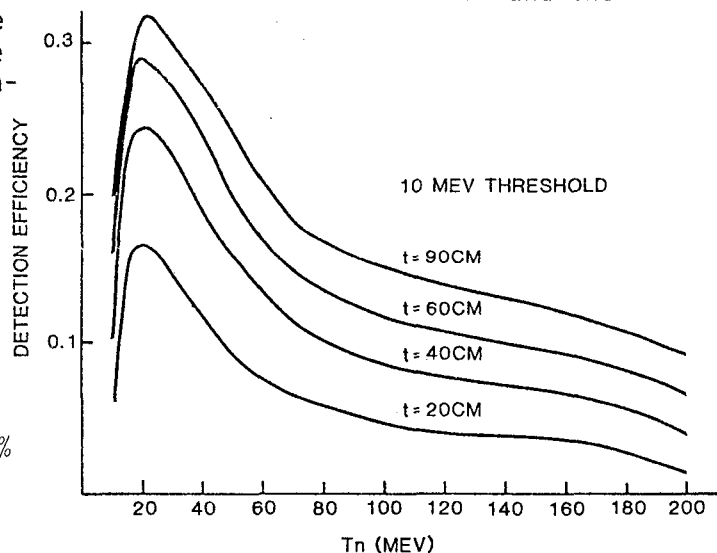


Fig. 3. Calculated detection efficiency as a function of neutron energy for an infinite slab of CH in the single scattering mode.

scattering mode particularly useful in determining the low energy portion of the solar neutron spectrum. This is especially important for small flares as the flux is reduced by neutron decay; e.g. 93% of the 20 MeV neutrons decay over the 1 AU flight path. Above 50 MeV the effective cross section for  $^{12}\text{C}(n,p) + ^{12}\text{C}(n,d)$  is greater than for n-p scattering. For a given neutron kinetic energy the protons observed at a particular angle have a distribution in energy extending from the maximum permitted by the reaction kinematics down to the threshold energy. In practice the deconvolution of the carbon protons will be less precise than that of the proton recoils where the width of the energy point spread function is due primarily to the instrumental energy resolution.

B. Double Scattering Mode. The detection efficiency for the double n-p scatters can be found by folding the single scattering results with the n-p angular distribution. The efficiency for a 60 cm thick infinite slab is 2% or greater over most of the 25-100 MeV range and  $> 1\%$  for  $T_n < 200$  MeV. This is two orders of magnitude greater than previous double scattering detectors where the energy and direction of both recoils were determined. Of comparable importance is the use of the  $90^\circ$  criterion to identify the first scattering as n-p. The neutron energy is given by  $T_n = T_p / \sin^2 \theta_n$  and the uncertainty by  $\Delta T_n / T_n = [(\Delta T_p / T_p)^2 + (2 \cot^2 \theta_n \Delta \theta_n)^2]^{1/2}$ . The second term is small because  $\Delta \theta \sim 10^{-3}$ . For  $T_n > 50$  MeV, the predominate contribution to  $\Delta T_p$  comes from the straggling in the proton range; therefore  $\Delta T_p / T_p < 1\%$ . The second proton may result from n-C rather than n-p without affecting the above analysis for solar neutrons. However if the source direction is unknown, the contamination of n-C protons will introduce an additional contribution to  $\Delta T_n$ . The energy and directional resolution can be determined by a Monte Carlo simulation or by an accelerator calibration of the instrument.

C. Calorimeter Mode. At 100 MeV the n-C inelastic cross section is a factor of three greater than the n-p cross section, increasing to a factor of six at 300 MeV. Although some of this energy escapes in secondary neutrons or  $\gamma$ 's and the various possible reactions have different Q values, a measurement of the ionization of the secondaries and/or their ranges can yield the incident solar neutron spectrum.

3. Response to Solar Flare Neutrons. The energy spectrum of the solar flare of June 3, 1982 has been determined over the range 20-1000 MeV in three separate observations (4,5,6). The neutron fluence for 20-200 MeV was  $500 \text{ cm}^{-2}$ . A 60 cm cubic SONTRAC detector would detect  $5 \times 10^4$  events spread over half an hour. During the same interval the atmospheric background could contribute  $\sim 10^2$  events within  $5^\circ$  of the sun. Thus a flare with neutron emission  $10^{-3}$  of the June 3, 1982 event would be detectable at the  $5\sigma$  level. Also of interest in the study of solar flares is the time correlation between neutron emission and the time structure of flare emitted electromagnetic radiation. The timing uncertainty is given by  $\Delta t = (\Delta T_n / T_n) \tau (\gamma + 1)^{-1} (\gamma^2 - 1)^{-1/2}$ , where  $\gamma$  is the Lorentz factor and  $\tau = 500\text{s}$  is the light transit time over 1 AU. For  $T_n = 100 \text{ MeV}$ ,  $\Delta t = 3\text{s}$ . This resolution is sufficient to resolve the 1 min time structure seen on some flares (4).

4. Location of Emission Region. The coded aperture mask technique has recently been applied to the imaging of high energy electromagnetic radiation. The complications introduced by a finite mask thickness and

only partial absorption in the mask have been considered in a similar context for high energy  $\gamma$ -ray astronomy (7). Because SONTRAC locates the neutron in the detector to an accuracy of 0.1 mm, the method is also applicable to the imaging of neutrons with an angular resolution determined by the pinhole geometry, as long as the mask cell size is large compared to the spatial resolution of the detector. For a cell size of 1 mm and a mask-detector separation of 50 m, the angular resolution is 4". At 50 MeV 10 cm of Fe gives 90% absorption. The mask vignetting angle of  $0.6^\circ$  is greater than the angular width of the Sun; thus the entire solar disk can be imaged with comparable resolution.

5. Discussion. SONTRAC has the sensitivity and energy resolution to measure the temporal neutron energy spectrum from solar flares over a dynamic range of  $10^3$ . This capability will make possible precision neutron measurements on a large number of flares during the next solar maximum. Determination of the neutron spectra for many flares will provide information on the statistics of ion acceleration, the acceleration time, the ion energy, the He content of the ions, the time dependence of the ion spectra, and possible beaming of the accelerated ions.

Observations of solar neutrons are best done from a satellite, since the long observing time makes it possible to detect a large number of flares in a low background environment. SONTRAC meets the criteria recommended for the neutron detector in the High Energy Cluster on the Advanced Solar Observatory (8). In the past it has not been practical to observe large flares from balloons because the flight times were at most of a few days duration and predictions of the flare time of occurrence were not reliable enough to give a reasonable probability of observation. Recently the RACOON technique has made it possible to obtain flights of several weeks duration (9). It has been found during the present solar cycle that large flares exhibit a 154 day periodicity (10). The combination of longer flight duration and cyclic flare occurrence make balloon observations of solar flare neutrons feasible. Flare observations from balloons have an advantage over satellites in that the 12 hr/day observation window is long compared to the flare duration. Therefore most flares will be observed in their entirety even though the neutrons are delayed in their arrival at the earth relative to the E-M radiation.

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