NEUTRON MEASUREMENTS IN SPACE

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Abstract. The experimental measurements of the neutron flux and energy spectrum in space since 1964 are reviewed and related to the theoretical predictions. A discussion of the neutron sources is presented. The difficulties associated with neutron measurements of both the atmospheric neutron leakage flux and solar neutrons are included. Particular emphasis is placed upon the neutron leakage flux and energy measurements at energies greater than about 1 MeV. The possibilities of CRAND as a source for the energetic trapped protons are discussed in light of recent measurements of the 10-100 MeV neutron flux. The current status of the solar neutron flux observations is also presented.

The primary purposes of neutron measurements in space have been to determine the neutron leakage flux from the atmosphere of the Earth and the solar neutron flux. As a consequence of the inefficient methods for neutron detection and the difficulties of conducting the measurements in the presence of the galactic and solar cosmic-ray backgrounds, the experimental results are very conflicting. It is the purpose of this review to interpret and discuss recent neutron measurements. In order to understand these results the theoretical predictions of the neutron fluxes and energy spectra from possible neutron sources will be briefly presented. Since comparisons of the different neutron measurements depend critically upon the experimental techniques, we will briefly discuss neutron detection methods applicable to space measurements. The emphasis will be upon measurements since 1964 made outside the Earth's atmosphere, but considerable reference will be made to high energy neutron experiments conducted within the Earth's atmosphere at <10 g cm\(^{-2}\) altitude. A review of earlier neutron measurements of terrestrial and solar neutrons has been made by Haymes (1965).

1. Introduction

The first observation of fast neutrons in the atmosphere was made by Rumbaugh and Locher (1936) who used paraffin-covered nuclear emulsions. Shortly afterwards Funfer (1937) detected slow neutrons in the atmosphere. A few years after these pioneering experiments Bethe et al. (1940) calculated the altitude and energy distributions of the neutrons in the atmosphere, a medium in which production, elastic scattering and absorption occur. Although Bethe and colleagues were principally concerned with the lower atmosphere, they did predict a maximum in neutron intensity at approximately 100 g cm\(^{-2}\) depth in the atmosphere, which agreed with later experimental measurements. In this theoretical analysis no attempt was made to evaluate the neutron leakage from the atmosphere. From 1940 to 1960 numerous experiments were performed, primarily by the New York University group under S. A. Korff (for detailed reference see Haymes, 1964), which yielded considerable data on the slow neutron flux in the atmosphere. Few experiments were conducted to measure the fast \((E_n > 100 \text{ keV})\) neutron intensity.

Experimenters were stimulated to measure the neutron flux and energy spectrum at the top of the atmosphere by the theoretical calculations of Hess (1959), Kellogg (1959) and Singer (1958a, b) which indicated that the neutron leakage from the terrestrial atmosphere with the subsequent decay of the neutron was the primary
injection mechanism for the geomagnetically trapped protons and electrons. However, the atmospheric leakage of neutrons produced by galactic cosmic-rays interacting with the atmosphere (the so-called cosmic-ray albedo neutron decay source: CRAND) has been found to be an insufficient source for the observed proton fluxes at $E_p < 20$ MeV. At energies $E_p > 20$ MeV recent experimental results indicate that CRAND may be the principal source of the trapped protons. As for the trapped electrons, the early observations of Pizzella et al. (1962), as well as the results of the Starfish explosion in 1962, indicated that CRAND could not be a primary source. However, the CRAND theory is attractive because relatively accurate calculations can be made provided that the neutron leakage flux and the atmospheric density at high altitudes are known. Solar flare protons will also produce neutrons in the atmosphere, a fraction of which will leak out. This source (referred to as solar proton albedo neutron decay: SPAND) has been shown to play no significant part in populating the trapped proton belt. One major difficulty with the earlier theoretical calculations was the paucity of measurements on the neutron leakage flux. Prior to 1963 only indirect observations had been made. Even today there are only a few experiments which have been actually conducted outside the atmosphere.

Before 1964 neutrons from sources other than the Earth's atmosphere had not been observed. Theoretical calculations (Lingenfelter et al., 1965a, 1965b; Lingenfelter and Ramaty, 1967), however, indicated that there should be a solar neutron flux comparable to or greater than the atmospheric leakage flux at $E \approx 30$ MeV. The difficulty of neutron detection at energies $E > 30$ MeV, the low predicted neutron flux at Earth, and the state of the art of scientific ballooning argued against the possible success of the earlier experiments. Recent developments, as we will indicate, make it more probable that if the solar neutron fluxes predicted actually existed, they should have been measured with the detectors of the sensitivity being flown.

In discussing neutron measurements in space, let us first consider the possible neutron sources, then the theoretical predictions of the neutron fluxes and energy spectra from these sources, and finally the experimental results. Particular emphasis will be placed upon interpreting the measurements of the atmospheric neutron leakage flux.

2. Neutron Sources

The three principal sources of neutrons in the region near the Earth are: (1) the atmosphere of the Earth; (2) the Sun; and (3) other sources outside the Earth–Sun region. These sources are indicated schematically in Figure 1. This phenomenological classification assumes the neutron measurements are carried out within a heliocentric sphere of radius $\approx 2$ AU. Close to the Earth, the Earth's atmosphere is the largest source of neutron energies $E_n \approx 30$ MeV. Of course, near other bodies such as the Moon there will also be a neutron leakage flux. There are two primary production mechanisms responsible for the atmospheric neutron leakage flux: (1) the interaction of galactic cosmic rays; and (2) the interaction of solar protons. At $E_n > 30$ MeV the calculations of Lingenfelter and Flamm (1964a, b) and Lingenfelter (1965a, b)