Revista Mexicana de Física 24 (1975) 87-95

# COSMIC RAYS AND NEUTRONS

Serge A. Korff

*New York University, New York, U.S.A.*

(Recibido: marzo 9, 1974)

ABSTRACT [*]: An historical survey is presented of two apparently quite separate topics in which the author has been personally interested. First, the general ideas of geomagnetic effects and the east-west asymmetry are outlined and it is recalled how the Lemaître-Vallarta analysis in that connection led to the discovery that the radiation consisted primarily of positively charged particles. Next, a brief history is given of the various neutron studies that have been performed since the 1930's to the present day, and a brief discussion is given of the effects of solar disturbances on the neutron intensity.

## INTRODUCTION

It is a great pleasure to have the opportunity to participate in the celebration of Dr. Manuel Sandoval Vallarta's seventy-fifth birthday. So much of what has transpired in the field of cosmic rays has been influenced by the work of this great scientist. His broad interests have touched many portions of this field, and all tributes to him which we have heard at this celebration are richly deserved.

In this report, I shall discuss two apparently quite separate topics in which I have personally been interested. The general treatment will be essen-

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[*] Supplied by the Editor.

tially historical. The two topics, while apparently quite diverse, are yet tied together by Dr. Vallarta's work and interests.

## GEOMAGNETIC EFFECTS AND THE EAST-WEST ASYMMETRY

My own first ventures into the cosmic ray field came about during the early 1930's. It will be recalled that the monumental work of Dr. Vallarta and his colleague Georges Lemaître, on the paths followed by charged particles in the earth's magnetic field[1] was published in 1933. This analysis served to explain an observation made by Professor J. Clay of Amsterdam, who had taken an electroscope from Holland to Java and had found a substantial decrease in the radiation while in the equatorial zone.[2] Actually, the latitude effect can also be seen in the atmospheric electric measurements made on board the non-magnetic ship, the Carnegie, some ten years earlier. However, no one had thought to plot the Carnegie data as a function of magnetic or rather, geomagnetic latitude, and the data remained buried for years. Clay's discovery, which could now be interpreted in terms of the Lemaître - Vallarta theory, led to the world surveys of A.H. Compton's group[3] and to a similar survey by R.A. Millikan's group,[4] with which I was at the time associated.

As a part of the Lemaître-Vallarta analysis, it followed that, in a certain energy interval, charged particles reaching the earth's surface would, if they were positively charged, appear to come in predominantly from the west, while if negative, they would come in similarly from the east. Thus the theory not only provided a test for the original question, whether the radiation consisted primarily of charged particles or of gamma rays, but also permitted experimental determination of the sign of the charge. The theory was therefore doubly valuable, in that it gave experimenters something very specific to measure, which could in turn provide two pieces of information. Several observers,[5] including myself, measured the east-west asymmetry, and concluded that the incoming radiation, at least in this energy interval, was primarily positive in charge. Since at that time the only positive particle known was the proton, the candidacy of the proton as the principal constituent of the radiation was of this origin. Later, when mesons were discovered, they were ruled out because of being radioactive. With a short half-life they could not, even with a very large relativistic time-dilation, have come from any distance. The proof that the primaries were not positive electrons came later from an analysis of secondary-production mechanisms.

At the time of my own visit to Mexico City, Professor Vallarta was at MIT, but I was warmly received and welcomed by Dr. R. Monges Lopez, an-excellent scientist and delightful friend. I set up my counters at the old Hotel Genève, in a room on the top floor, from the window of which I could see mounts Popocatépetl and Ixtaccíhuatl. By varying thicknesses of lead between the counters and in front of the counters I tried to narrow down the energy intervals involved. From Mexico I proceeded to Perú, where I repeated the experiments at three different elevations. In all cases a west excess was found which could be fitted into the Vallarta picture.[6,7]

## NEUTRON STUDIES

Neutrons are generated by the cosmic radiation as the primaries impact upon the nuclei of nitrogen and oxygen in the upper atmosphere. Probably the first indication of neutrons came from an experiment performed by Rumbaugh and Locher,[8] who flew an emulsion in the National Geographic balloon flight Explorer, which on November 11, 1935 attained a then record-breaking altitude of 72,395 feet above sea level. They found, upon examining the emulsion, numerous tracks which they identified as recoil protons, which in turn they attributed to being secondaries recoiling from fast neutrons. Today it is generally felt that this identification is probably correct, but at the time little attention was paid to that interpretation.

At the time, I was at the Bartol Research Foundation, as were also Locher and Rumbaugh. Encouraged by W. F. G. Swann, the director, and by G. N. Lewis who stopped by for a visit, I resolved to try to make some direct measurements of a slightly different type, using a technique which would overcome the criticism that there were many ambient protons in the region where the tracks had been observed. To this end I built a proportional counter, filled with the gas $BF_3$, in which a slow neutron would generate an alpha particle, which in turn could readily be distinguished from protons by virtue of its higher specific ionization. With such counters the diminution in counting rate achieved by surrounding the counter by a millimeter of cadmium would clearly distinguish the neutron-capture alphas from other highly ionizing entities. I flew such counters in a series of balloon flights from the roof of the Bartol building, and found that there was a very rapid increase of neutron counting rate with altitude.[9] Later I also flew a proton-recoil counter, a proportional counter filled with methane, and concluded that there were also fast neutrons in the upper atmosphere. In the meantime, a number of other observers, using various detection techniques, reached similar conclusions.[10]

The next problem was to relate, quantitatively, the observed counting rates with the neutron flux or density in the atmosphere. This study was undertaken and led to a lengthy paper by Bethe, Korff and Placzek.[11] In this paper it was pointed out that any detector with a $1/v$ sensitivity measured the density and not the flux of neutrons. Further, if the neutrons were absorbed by some nucleus also with a $1/v$ energy dependence, the counting rates would determine the rates of production of the neutrons in the atmosphere. Since the neutrons were radioactive, they could not have come from any great distance, and so were not primary particles. We shall return to this point later. The neutrons are produced by impacts of the primaries, mostly protons, and some alphas, on the nuclei in the upper atmosphere, which in turn consists of approximately 80% nitrogen, 19% oxygen and 1% argon. The neutrons emerge from the target nuclei with a spectrum containing a few very fast neutrons, many of the order of a few Mev's, and some slower ones. They are slowed down by subsequent collisions with other nuclei, which are at first inelastic and reduce the projectile energy rapidly. Once the neutron energy is below the lowest energy level in the target nucleus, the collisions are elastic and can be treated by classical billiard-ball mechanics.

Finally the neutrons, once slowed, are absorbed by the various nuclei they encounter. The principal such mechanism is the $(n,p)$ reaction in ordinary nitrogen, which generates the famous carbon 14 in the atmosphere. This process and all its consequences has been so fully discussed that it will not be repeated here. Libby's Nobel prize work in this field makes further discussion trivial.

What was not known in 1939 was that, in addition to slow neutron capture by this process, the nitrogen nucleus contained a set of resonances which permitted capture at higher energies to form radiocarbon. These neutrons were therefore captured before they had been slowed down to that energy range to which our counters were sensitive. This led to a discrepancy between our measurements of neutron production rates derived from the slow neutron detector and the carbon 14 generation rate observed by the people who measured radiocarbon. Over the years, as the nitrogen cross sections became better known this discrepancy in due course vanished.

Other substances produced by neutron capture also include tritium and beryllium 10, the latter being also produced by direct spallation of nitrogen and oxygen by the primaries. Tritium was identified, following our prediction, by v. Grosse, and $Be^{10}$ by Peters.[12] At present T is of less value as a dating tool because there is a lot of man-made tritium in the atmosphere. It can, however, be identified deep in glaciers, and has been used to study water movements in the deep ocean. But as for radioberyllium, with its 2.5 million year half life, which is just what is needed in geology, my prediction is that a development of the technique for using this substance would be of the greatest value to geological science.

Another problem which soon emerged in the cosmic ray neutron measurements was that the $BF_3$ counters actually measure all of the ionizing events taking place inside the counter. This means that they measure, in addition to the alphas resulting from neutrons, a background consisting of all highly ionizing events. These include ambient particles of high specific ionization, and also nuclear disintegrations taking place in the walls of the counter which in turn send highly ionizing fragments through the gas. The solution of this problem came about owing to the development of isotope separation techniques.

The element boron in nature consists of two isotopes, $B^{10}$ and $B^{11}$. The $B^{11}$ is four times as abundant in nature as the $B^{10}$, but only the $B^{10}$ isotope is capable of undergoing the $(n, \alpha)$ reaction which is the basis of the neutron detection process. It was realized early in this work that if it were possible to obtain some $BF_3$ in which the B was entirely $B^{10}$, this gas would make a counter five times as efficient as one made with ordinary boron. The Oak Ridge Laboratory was in due course persuaded, after much correspondence, to produce isotopically enriched $BF_3$. They produced this with a 96% enrichment. In this enriching process, some isotopically depleted B was also generated, and after even more correspondence, some gas was made available, in which the $B^{10}$ was down from the normal 20% to 10%. This made it possible to fill two identical counters to the same pressure, one with enriched and one with depleted $BF_3$. With these two counters symmetrically disposed with respect to the batteries and other heavy possible sources of secondary particles, it might reasonably be assumed that the backgrounds in the two counters were identical. The counting rates of the two counters therefore permitted determination of two variables: first, the counting rate of a counter detecting neutrons with full efficiency, and second, the background.[13]

Flights were made with this system. The measurements of the neutrons now fitted much better, especially at high altitudes. The background due to highly ionizing events was found to have a much higher transition maximum than had been previously thought.

With the development of scintillation counting techniques, it became feasible to make fast neutron measurements as well as to measure slow neutrons. The poor efficiency of a recoil proton counter when filled with a gas was improved by three orders of magnitude by using a scintillating solid. Further, such a counter permits a spectrum of the neutrons to be determined, in the range interval bounded on the upper limit by the size of the detector and on the lower by the small pulses due to noise, electrons and gammas. To this end we developed a scintillator, which, since it had to be used in an environment where there were many ambient protons, had to have an anticoincidence shield in addition.[14] Our detector was designed to operate in the interval between 1 and 10 MeV.

With this detector we made a series of flights at various latitudes, throughout the atmosphere.[15] This, combined with a similar survey made with slow neutron measurements,[16] even to and including a rocket flight up to 200 kms. altitude,[17] gave us a good picture of the latitude and altitude dependence all over the world. The neutrons turned out to be a good and sensitive means of fitting the spectrum of the incoming radiation to Vallarta's equations. It also gave a good determination of the global rate of production of radiocarbon.

During these latitude surveys we noted that the neutron intensities appeared to be time-dependent. The immediate suggestion that came to mind was the possible dependence on the state of the sunspot cycle. In essence, what happens is that during sunspot maximum, or solar activity maximum, the sun emits a larger and more irregular solar wind of electrified particles than during periods of the quiet sun, or solar activity minimum. These particles, by virtue of their motion, generate a magnetic field which in turn modulates the flux of primary particles, originating beyond the solar system.

We therefore made a series of flights over the sunspot cycle between about 1959 and 1970. Most of these flights were made at far northern latitudes, either from Fort Churchill, Manitoba, Canada, or from central Alaska near Fairbanks.[18] The reason for this is that the variations are larger in these regions than in the equatorial zone. The lower geomagnetic cutoffs, following the Vallarta analysis, give the largest amount of information.

During this work it was also found that solar flares, or to be more specific, solar disturbances, produced occasional very large effects on the neutron intensity. There are in the main two quite different effects. The first is an increase, usually starting very abruptly, going in some cases up to large values, such as factors of two or more at sea level, and then decreasing over a few hours back to normal. The second is a diminution, following the well-known Forbush type decreases which have been known for nearly forty years in the ionizing component of the radiation. We studied both these variations.[19]

The effects are rather complex. There are probably at least three effects to be considered. The first is the arrival of protons from the sun, emitted in solar disturbances and of sufficient energy to generate neutrons when they impinge on the earth's atmosphere. The second is the magnetic field generated by the solar wind and its modulation of radiation entering from a great distance. The third is the effect of the solar wind in altering the earth's field and thus changing the cutoffs of the galactic radiation. The latter two mechanisms are closely intertwined. We have, for instance, noted increases in neutron counting rates at balloon altitudes occurring during an auroral display, at a latitude (northern Minnesota) at which such displays are rare.[20]

Neutrons originating in the sun have been sought by our group and by others, with so far inconclusive results. With the sun about 8 light minutes away, and the neutron radioactive half-life only a little more, a neutron with 10 MeV starting at the sun has a chance of 3.7% of surviving to reach the earth. At larger energies the percentage increases fast, aided by the relativistic time-dilation of the lifetime.[21] Certainly in the violent processes on the sun there must be neutrons generated, at least by charge-exchange scattering, and probably other mechanisms as well. People have even wondered whether neutrons at very high energies from distant sources could get here. However, at $10^{15}$ eV the limit is 30 light years, no very large distance in astronomy. Clearly additional work on neutrons of solar origin could be of interest in years to come.

The work of the man whom we are honoring today has been fundamental in much of what has transpired since then.

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## RESUMEN*

Se presenta una visión histórica de dos tópicos aparentemente muy separados, en los cuales el autor ha tenido interés personal. Primero se mencionan las ideas generales de los efectos geomagnéticos y la asimetría este-oeste y se recuerda cómo el análisis de Lemaître-Vallarta en esa conexión llevó al descubrimiento de que la radiación consiste principalmente de partículas cargadas positivas. En seguida se presenta una breve historia de los estudios sobre neutrones que se han llevado a cabo desde la decada de los treintas hasta nuestros días y se discuten brevemente los efectos de los disturbios solares en la intensidad de los neutrones.

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[*] A cargo del editor.