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ELEMENTARY PARTICLES AND FIELDS
Experiment

Study of Environmental Thermal Neutron Fluxes: from EAS to Geophysics

Yu. V. Stenkin[1)]*

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Abstract—Environmental neutrons originate from two sources: cosmic rays and natural radioactivity. They are in equilibrium with media and are therefore sensitive to many geophysical or Sun–Earth–Moon phenomena in accordance with the source of production. A history and some results obtained with the neutron technique are overviewed and discussed. The electron–neutron detectors (en-detectors) were developed at INR RAS in the framework of the PRISMA project to study Extensive Air Shower (EAS) hadronic component through thermalized neutrons. By continuous monitoring of neutron background with the en-detectors we have found interesting variation effects in the environmental thermal neutron flux, caused by geophysical phenomena. As shown, environmental thermal neutron flux could serve as a useful instrument to study cosmic rays, geophysical phenomena and many other applications.

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1. INTRODUCTION

Neutrons are known many years and are very abundant in the Nature, but are used up to date mostly for neutron physics study and to study its own properties having fundamental significance. They also are used in industry for neutron imaging, neutron logging in geology, etc. On the other hand, their usage as an instrument for environmental study is still very limited. In this work, we try to overview the history and some applications of measurements with environmental neutrons. The latter can be subdivided into two parts: a) high energy measurements where neutrons are generated by high-energy cosmic rays and b) low energy measurements when neutrons produced by natural radioactivity are in equilibrium with media and thus can give information about the media state and its dynamics.

Environmental neutrons being a useful instrument could join a lot of different sciences and phenomena in Nature, such as cosmic rays, geophysics, geology, Earth–Moon–Sun relations, Earth's inner structure, earthquakes, Earth free oscillations, etc. This could be illustrated by a schematic picture shown by V. Alekseenko in 2018 at WASDHA2018 Workshop (http://wasdha2018.inr.ac.ru/programme/talks/Alekseenko_Victor.pdf) (Fig. 1).

2. NEUTRONS IN EAS

2.1. Historical

Up to the middle of previous century, it was thought that Extensive Air Shower (EAS) is an electromagnetic cascade developing in atmosphere. Experiments carried out by V. Tongiorgi under the guidance of Cocconi [1, 2] had shown that nuclear active particles (nowadays called hadrons) are present in EAS as well. They have found generation of neutrons in targets made of lead, carbon, etc, and correctly estimated fraction of these particles at a level of few percent. These and other works as well as

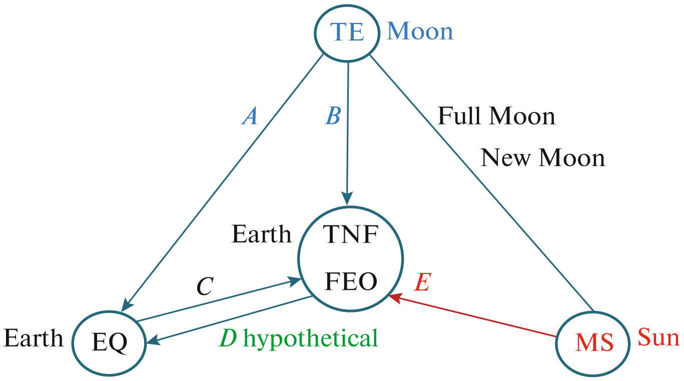

Fig. 1. Schematic triangle showing ties of environmental neutron flux with Natural objects and phenomena. TE—tidal effect, EQ—earthquake, MS—magnetic storm, FEO—free Earth oscillations, TNF—thermal neutron flux; A, B, C, D, E—ties between the phenomena and TNF or/and FEO response.

[1)] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia.

[*] E-mail: `stenkin@sci.lebedev.ru`

contradictions in experimental data led G.T. Zatsepin [3] to a conclusion that EAS is a hadronic cascade where hadrons constitute a *shower skeleton* while electromagnetic particles, being a secondary component, originate from decays of neutral pions. The equilibrium between EAS components lasts while cascading hadrons (N_h) do exist. However, as we know N_h is rather small in comparison with other particles. K. Greisen later mentioned this [4] saying that N_h can be as small as one. This results in large fluctuations in EAS development, where hadrons play a role of the EAS backbone. However, we could argue here that nothing prohibits a case of $N_h = 0$. This is a final stage of hadronic cascade development when the last cascading hadron lost its energy to a level below the threshold for pion production. We called these showers as *coreless* EAS [5, 6]. Existence of this stage has a principle meaning for EAS phenomenology as it dramatically changes EAS properties and produces a knee in the EAS size spectrum at $Ne \sim 10^6$ even at pure power law primary spectrum. Below this size, depending on measurement altitude and selected zenith angles, the EAS method does not work properly, thus putting a lower limit to its correct usage. The reason is that core location of the coreless showers cannot be made correctly and this results in primary energies recovering of showers being in the coreless stage is also not correct. Only measuring of hadronic EAS component allows one to recognize the stage of EAS development and exclude coreless ones. That is why EAS neutron measurement is strongly needed for correct spectrum recovering in PeV region.

Many years ago Greisen emphasized [4] that neutrons produced by EAS hadrons are “very abundant in the showers, but have not yet been measured.”

2.2. Experimental

New interest to the neutron measurements in EAS appeared when in the 1990s Lebedev Institute group claimed about anomalies in EAS neutron distributions as measured by Tien Shan Neutron Monitor [7, 8]. The latter stimulated us to repeat their measurements. As a result, we found that all “anomalies” could be explained by methodical reasons caused by poor time resolution of gas counters [9, 10]. On the other hand, the phenomenon, which we called as “Neutron bursts,” does exist. After understanding that neutron bursts are associated with EAS passage we proposed to use EAS thermal neutrons as a calorimetric parameter and energy estimator [11, 12] extending the EAS method for ultra-high energy cosmic ray study.

Later we developed electron–neutron detector (en-detector), a Compact Multi-Component EAS array (MultiCom) had been proposed [11] and then we proposed the PRISMA project (PRImary Spectrum Measurement Array) [13]—a novel type of EAS array measuring hadronic component over full array area.

First long time working array of such type (PRISMA-32) [14] consisting of 32 en-detectors has been constructed in collaboration with the NEVOD experiment group in MEPhI. Many-neutron EAS component parameters, such as its lateral and temporal distributions, have been studied using this array. Later preliminary primary spectrum above 1 PeV has been recovered using EAS thermal neutrons as energy estimator [14]. Similar investigations were made at high altitude using a small prototype array PRISMA-YBJ located in Yangbajing (Tibet, PRC) on a base of ARGO-YBJ experiment [15, 16]. These measurements as well as simulations have shown that primary cosmic ray energy where fast rising of neutron production is observed, coincides with hadrons appearance at observation level and coincides with the “knee” region independently of the observation level altitude. This confirms our previous claim that the “knee” is connected with a transition of coreless showers to normal EAS [5]. That is why measurement of the main (primary) EAS component (hadronic) is strongly needed for correct recovering of primary cosmic ray spectrum and mass composition in this energy region.

Currently we started construction of a full-scale experiment of the PRISMA type in collaboration with the LHAASO experiment at an altitude of 4410 m (http://english.ihep.cas.cn/lhaaso/). It will be so-called ENDA array (Electron–Neutron Detector Array) consisting of 400 en-detectors with 5-m spacing [17, 18]. Working in conjunction with other LHAASO detectors it will have an outstanding performance making it possible to solve the “knee problem.” Developed novel method of mass composition measurement using n/e ratio measured by the same detector and machine learning technique will help us to do it.

3. ENVIRONMENTAL NEUTRONS’ VARIATIONS AS A WAY TO GEOPHYSICAL RESEARCHES

3.1. History

Early understanding of neutrons in surrounding environment came very soon after neutron discovery in 1935. In the work of Bethe et al. [19] first calculations and estimations were made of neutron fluxes in atmosphere. As it was found, neutrons do not fly far from the point of their production due to energy loosing through scattering and then capturing after the moderation process.

In early 1950s experimental study of environmental neutron fluxes led to developing of the Neutron Monitor (NM) and to construction of a global net of these devices to study low energy cosmic ray variations [20]. However, the NM records secondary neutrons produced inside the NM lead target (producer), then moderated in organic hydrogen containing material (moderator) and captured in boron proportional counters. Probability of outside thermal neutron to be recorded by this device is as low as $\sim 10^{-4}$ due to thick outer layer of moderator. It was specially made to make NM insensitive to outer neutrons. Why? Because environmental thermal neutrons are in equilibrium with media and are sensitive to its changes, while the purpose of the NM developer was making of a stable device to study cosmic rays. However, inverse task could be put: make a device sensitive to the media state with a purpose to study geophysical phenomena using nuclear physics methods. This led us to using the en-detectors for these studies.

3.2. Experimental Study

Attempts of experimental study of environmental thermal neutron fluxes with unshielded neutron counters were made from time to time in different countries starting from the middle of the 20th century. In the Soviet Union probably the first measurements of such types were made by Gorshkov et al. (see [21] and references therein). It is interesting that they used an open scintillator detector based on ZnS + boron compound very similar to what we are using in our en-detectors. They showed that neutrons near soil surface are mostly produced by cosmic rays interacting with the soil nuclei. This also means that neutron flux above water surface is much less. Natural radioactivity was also mentioned as a neutron source.

Then a group from Skobeltsyn Institute led by Kuzhevskij started a systematic study of environmental thermal neutron fluxes using open helium neutron counters [22, 23]. In these and other their works they put attention to a possible correlation of environmental thermal neutron flux with geophysical phenomena, such as earthquakes, tidal waves, solar eclipses, etc. Unfortunately, stability of the gas counters was poor and as a result counting rate changed by more than 2 orders of magnitude during one measurement. Nevertheless, these works pushed us to this study.

3.3. Study of Geophysical Phenomena Using en-Detectors

The en-detector has been firstly developed for measuring of neutron component in EAS. It is based on a thin scintillator compound ($ZnS(Ag)$ + ^6Li or ^{10}B) layer (30–50) mg/cm^2 of 0.36 m^2 area viewed by one PMT. By monitoring neutron background at the measurements site, we found that en-detector is very stable device suitable for variation measurements. Moreover, usage of pulse shape separation technique makes it possible to monitor not only neutron flux but as well concentration of beta-decay activity in vicinity of the detector, caused mostly by decays of radon in air. The features of the en-detectors are strengthened also by full pulse shape digitizing and analysis, allowed us to find a number of interesting effects in geophysics using nuclear physics methods. The most interesting founded effects are listed below.

3.3.1. Neutrons in thunderstorms. Many "evidences" for neutron production by lightning were published in last two decades. As known, lightning could produce neutrons in photonuclear reactions only in a case if energy of produced gamma-quanta is higher than $\sim$20 MeV. In addition, suitable target should exist (with high Z) in vicinity of detector where flux of such high energy gammas is enough to generate neutrons and recording efficiency of the detector is enough to record them. Up to date nobody has shown existence of such gammas produced by lightning. On the other hand, lightning produces short and strong pulse of current with 100% probability. As a result, every bolt produces strong electromagnetic noise, sometimes even dangerous for electronic devices. It is clear that only detector's pulse digitizing and full pulse shape control can prevent false hits. Unfortunately, very few experiments follow this rule. Our measurements have demonstrated absence of thermal neutron excess during thunderstorms [24]. Moreover, sometimes decrease of thermal neutron flux was observed if before the thunderstorm there was a dry period. In this paper, we have also shown how false "excess" could be observed. Accordingly Armenian group have shown [25] that pulse shape digitizing and selection led them to understanding that previously published result about "neutron excess" was wrong. Recent measurements of Irkutsk group [26] also demonstrated a role of electromagnetic noise recorded by NM counters during thunderstorms.

3.3.2. Neutron tidal waves. Earth's crust is one of the two neutron sources due to its natural radioactivity. α-active nuclides produce neutrons in (α, n)-reactions on suitable target nuclei existing in rock and soil. Radon (especially long living Rn-222) plays a special role in this process: it produces a number of α-active shortly living daughter nuclides and it can migrate for rather long distances in soil and rock along with other soil gases. Radon diffusion length depends strongly on the soil porosity and fracturing. The latter depends in its turn on any soil vibration and movement. Consequently, neutron production in crust depends on seismic activity and even on lunar tidal forces. As known, an amplitude of semidiurnal tidal wave in crust is only ∼40 cm. It is much less than it is in oceans, but it is enough to increase soil porosity and thus to increase local radon concentration and neutron production as it was established in our works [27–29]. It should be noted that amplitudes of lunar tidal waves [29] are very small ($\leqslant 0.5\%$) and to find it the detector should have good longtime stability and all pulses should pass corresponding pulse shape filters.

3.3.3. Neutron pumping effect. Barometric pumping effect is known for geophysics for a long time. When air pressure goes down, all soil gases (air, methane, radon, etc.) are pumping from deeper soil or rock layers to atmosphere. As shown above, neutron flux is dependent on radon local concentration in surrounding soil. Consequently, neutron production underground should depend on barometric pressure. As it was shown [30], the barometric pumping effect does exist not only for gases but for thermal neutrons as well. The difference between effect for neutrons and for gases is only in the delay from the starting point of pressure decreasing to measuring value increasing. For neutrons we obtained 24 h delay, but it depends on real soil porosity, on the depth of observation (surface or underground), etc. In a case of underground laboratory measurements, the effect depends strongly on gases' penetrability to the laboratory volume. In our case, it was a simple underground room at a depth of 10 m without ventilation and without hydro- or gas-isolation. Neutrons' diffusion length in soil (rock) is equal to few meters and thus its concentration depends on radon concentration at these shallow depths. Even thermal neutrons can pass this distance very quickly and observed delay is explained by radon diffusion velocity, not neutron one. When air pressure starts decreasing, then radon diffusion starts from the nearest layer to current layer, then from deeper layer and so on. This is slow process depending on many parameters. In our case, we obtained 2-day delay and called the effect as "delayed barometric pumping effect for neutrons." Barometric coefficient calculated taking this delay into account, is as large as −5.5%/mm Hg. In our opinion, the effect must be taken into account in low background underground experiments.

The array contains also gamma-ray detector based on CsI crystal. When analyzing its data, similar effect has been found for gamma background radiation, namely nonlinear delayed pumping effect. We have to note here that in comparison with a total gamma background, gammas from radon chain decays look as a small addition if one does not select specific energy peak regions. Usually we do not see pumping effect in counting time series of gammas. However, there exists nonlinear pumping effect [31]. The ordinary pumping effect is following: in the presence of periodic fluctuations of some parameter (temperature, pressure, etc.) at a border between two media, the parameter inside a medium changes periodically with amplitude proportional to that at the border but with delayed phase. The nonlinear pumping effect consists in a nonlinear (quadratic) dependence of the pumping-out on the amplitude of periodic fluctuations at the two-media border thus emphasizing large fluctuations. Therefore, we observed the effect only due to abnormally low barometric pressure in Moscow in February 2020. Analysis of the excess energy spectrum has shown a presence of the specific nuclides of Rn-222 chain [32].

3.3.4. Neutron response to earthquakes. As we learned it above, environmental thermal neutron flux is sensitive to crust dynamics. Therefore, it is naturally to suppose that it should be sensitive to earthquakes. The question is: could thermal neutron flux dynamic serve as a predictor or only as an indicator? To answer the question, one needs first to show correlation between the earthquakes and any parameter associated with neutron flux in a time vicinity of earthquakes.

To answer the above question we located our en-detector arrays at seismically active regions—at Tibet (PRC) and later at Kamchatka (Russia). PRISMA-YBJ array consisting of 4 en-detectors run in Yangbajing (Tibet) from 2013 to 2017. As known, the catastrophic Nepal earthquake ($M7.8$) happened in April 2015 and a response of thermal neutron flux to this event had been recorded [33, 34]. Epicenter of the main earthquake occurred at a distance of ∼600 km from Yangbajing. Many aftershocks (maximal $M7.3$) lasted more than 2 weeks were spread over a large area. The response of thermal neutron flux was not simple, probably due to a large epicenter distance. We did not record any excess in neutron count time series. However, the response was recorded in a parameter indicating diurnal wave phase both for neutrons and for so-called "charged" component sensitive to radon decays in air. Usually the diurnal waves for neutrons and "charged" anti-correlate but, in the day of strong earthquakes (or in next day) phases of these waves changed and they began to coincide. It should be noted that shape and phase of diurnal wave are different in different geological locations and still not understood. This question should probably be addressed to geologists. Anyway, earthquakes change it and this can be an indicator of earthquakes, not a predictor. Sure, the main goal for scientists is finding a predictor. Attempt to find a response of radon concentration measured in the same experimental hall gave no results due to existence of many false "alarms" produced by standard radon meters [34]. In contrary, neutron flux analysis gave only 6 alarms for a period of 3.5 years and only for 2 of them the reason was not identified.

New investigations should be performed and environmental thermal neutron flux looks as a perspective parameter to be carefully analyzed as a possible predictor.

4. CONCLUSIONS

We tried to show here that environmental thermal neutron flux could be used for many applications, serving as an instrument to study cosmic rays and geophysical phenomena in addition to fundamental neutron physics and technical applications. Nuclear physics methods applied to other sciences could give new results unreachable by other methods. Sure, the list of applications shown above is not full and will undoubtedly be expanded in the future and many new ties between phenomena shown in Fig. 1 will be established.

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