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UNDERGROUND INVESTIGATION OF EXTENSIVE AIR SHOWERS SPECTRA AT HIGH ENERGY RANGE OF COSMIC RAYS AND OTHER RESEARCH IN THE PYHÄSALMI MINE

High energy particles reaching the Earth's atmosphere are known as cosmic rays. As a result of interactions with nuclei of air molecules, cosmic rays induce showers of secondary particles, which can be divided into 3 components: electromagnetic, hadronic and muonic components. The Experiment with Multi Muon Array (EMMA), located at the depth of 75 m in the Pyhäsalmi mine in Finland, investigates the muonic component of the Extensive Air Showers (EAS) to deduce the direction, energy, and the mass of the primary cosmic ray particles. In this paper we give a concise description and methodology used by EMMA followed by a brief review of the C14 experiment. Finally, we review the feasibility to host in the Pyhäsalmi mine a future large-scale liquid-based neutrino detector and implement a novel concept of acoustic detection of neutrinos in bedrock utilizing the network of many kilometers of boreholes surrounding the now-exploited ore body.

Key words: high-energy muon, cosmic rays, Extensive Air Shower (EAS), knee, EMMA.

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Pyhäsalmi шахтасындағы ғарыш сәулелерінің жоғары энергетикалық диапазонында кең ауқымды нөсер спектрлерін жерасты зерттеу

Жер атмосферасы арқылы өтетін жоғары энергия бөлшектерінің ағыны ғарыштық сәулелер ретінде белгілі. Жоғары энергетикалық ғарыш сәулесі бөлшектерінің ядролық өзара әрекеттесуі нәтижесінде екінші реттік бөлшектер өндіреді, оларды 3 құрамдас бөлікке бөлуге болады: электромагниттік, адрондық және муондық. Финляндиядағы Пюхясалми шахтасында 75 м тереңдікте орналасқан мульти-муон массиві (EMMA) бар Эксперимент бастапқы ғарыш сәулесі бөлшектерінің бағытын, энергиясын және массасын шығару үшін кең әуе нөсерлерінің (EAS) муондық құрамын зерттейді. Бұл мақалада біз Эмма қолданатын қысқаша сипаттама мен әдіснаманы, содан кейін C14 экспериментіне қысқаша шолу береміз. Ақырында, біз шахтада болашақ ірі көлемді сұйық нейтринді детекторды Пюхясалми орналастыру мүмкіндігін қарастырамыз және қазіргі қолданыстағы кең көлемі көптеген километрлік ұңғымалар желісін пайдалана отырып, жартастағы жыныстардағы нейтриноны акустикасын анықтаудың жаңа тұжырымдамасын іске асырамыз.

Түйін сөздер: жоғары энергиялы муон, ғарыш сәулелері, кең ауқымды нөсер (КАН), тізе аймағы, EMMA

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Подземное исследование спектров широких атмосферных ливней в высокоэнергетическом диапазоне космических лучей в шахте Pyhäsalmi

Частицы высокой энергии, достигающие атмосферы Земли, известны как космические лучи. В результате взаимодействия с ядрами молекул воздуха космические лучи вызывают потоки вторичных частиц, которые можно разделить на 3 составляющие: электромагнитную, адронную и мюонную. Эксперимент с мультимюонным массивом (EMMA), расположенным на глубине 75м в шахте Пюхясалми в Финляндии, исследует мюонную составляющую широких атмосферных ливней (EAS) для вывода направления, энергии и массы частиц первичного космического луча. В этой статье дается краткое описание и методология, используемая EMMA, а затем краткий обзор эксперимента S14. В итоге, рассматривается возможность размещения в шахте Пюхясалми будущего крупномасштабного жидкостного нейтринного детектора и реализуется новая концепция акустического обнаружения нейтрино в коренных породах с использованием сети многокилометровых скважин, окружающих ныне эксплуатируемое рудное тело.

Ключевые слова: высокоэнергичный мюон, космические лучи, широкий атмосферный ливень (ШАЛ), колена, EMMA.

Introduction

The existence of the “knee” in the energy spectrum of the cosmic rays has been discovered decades ago but still awaits a satisfactory explanation. Several models have been proposed to explain the bend in the spectrum, but the experimental data are still insufficient to allow for conclusive analysis. The flux of CR has very steep energy dependence. While at the low-energy end of the spectrum it is possible to make direct measurements of CR using detectors mounted on satellites or high-altitude balloons, the only way to study CR at or above the knee energy of 10^{15} - 10^{16} eV is by measuring the properties of the Extensive Air Showers (EAS) using large-area ground-based arrays. The largest of them are the Pierre Auger Observatory [1], the recently decommissioned KASCADE-Grande [2], and the still under construction LHAASO experiment [3]. Especially relevant for the understanding of its origins would be information on the mass composition of the primary cosmic ray (CR) particles. It would probe the hypothesis explaining the knee as a manifestation of the switch between the proton-dominated flux into the iron-dominated flux of CR. As the extraction of the mass of CR from the EAS components is heavily model-based, it is important to use complementary experimental techniques to address this issue.

Experiment with Multi-Muon Array (EMMA) is the first low-depth underground cosmic rays experiment dedicated to the study of the mass composition around the knee. The EMMA setup is able to probe the lateral distribution of underground muons up to high muon multiplicities. The energy of the primary CR is deduced from the core density and the mass, from its slope. Since the simulations using different air-shower models give similar predictions for the lateral distribution of these high-energy muons, we are confident that EMMA should yield reliable and model-independent data on the composition of cosmic rays around the knee region [4].

The Pyhäsalmi mine

The Pyhäsalmi mine (63°39.6 N, 26°02.5 E), located close to the geographical center of Finland, is the deepest metal mine in Europe reaching down to 1.4 km below the surface. Because of the compactness of the ore deposit, very good mechanical properties of the surrounding rock, modern infrastructure, safety record, and cool temperature, the mine would be an ideal site for future large-scale scientific projects [5][6].

The main level of the mine, where all the major facilities are located, is at 1400 m underground. These facilities, now scheduled for gradual

decommissioning following the end of the ore excavations in 2019, include four large halls designed for storage, service and maintenance of mining machinery. There are also control rooms, social areas and a restaurant. The 1400 m level is accessible from the ground level by an elevator and by a 12-km long truck-size decline. The elevator ride takes about three minutes while a car ride lasts about half-an-hour. In addition to the main level, there are additional large caverns at the depths of 990, 660 and 400 m.

Currently there are two physics experiment collecting data in the mine: the cosmic ray experiment EMMA at the depth of 75 meters and, at 1410 meters, a radiopurity setup probing the content of ^{14}C in liquid scintillator samples coming from or intended for neutrino experiments such as Borexino [7], SNO+ [8], and JUNO [9].

Experiment with Multi-Muon Array

The EMMA array consists of 11 detector stations, as shown in Fig. 1, situated at the depth of 75 meters in the Callio Laboratory of the Pyhäsalmi

mine, Finland. The three central stations have extended tracking ability with the increased height (flight path) and with segmented, high-granularity scintillator detectors in the middle. The remaining 8 stations are called sampling stations as their tracking performance is inferior, but still sufficient to correlate with the events registered by the tracking stations. In addition to drift chambers and plastic scintillation detectors, there are plans to extend the instrumented surface of EMMA with limited streamer tubes. The gas required for the operation of the drift chambers is supplied from a large liquid gas tanks on the surface via a 90 m borehole. The array is able to measure muon multiplicity (the number of muon tracks), their lateral distribution and the arrival direction. The shower core can be located with an accuracy better than three meters in the central area of 300 m^2 registering a couple of knee-region air showers per day. The arrival direction (zenith and azimuth angles) of air showers is determined by the tracking stations with an accuracy of 1 degree. This is important as the direction relates to the effective rock thickness (for vertical muons, it is 75 m) and consequently to the muon energy cut-off.

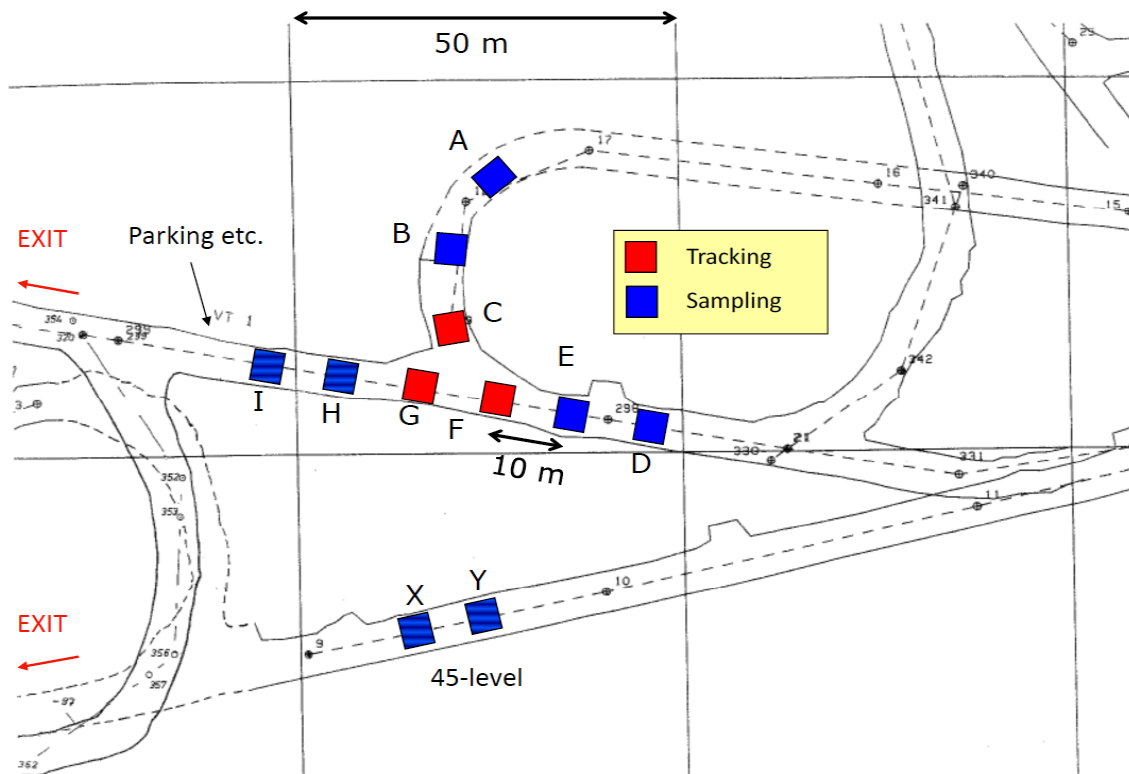


Figure 1 – Schematic layout of the detector stations of the EMMA array. The footprint of each station is about 15 m^2 . The key tracking stations: C, G, and F are at the depth of 75 meters. The stations X and Y are at 45 meters.

3.2. EMMA detection system

The main detector types used by EMMA are: drift chambers [10] and plastic scintillation detectors [11]. The former is the primary detector of the experimental setup providing the total active area of approximately 240 m². The drift chambers used by EMMA have been recovered from the decommissioned DELPHI experiment [10] at CERN LEP collider. They were designed and built for muon tracking. The plastic scintillation detectors with the total coverage of approximately 24 m² were designed as ancillary detectors for EMMA but they can also be used in other underground measurements [12]. Funding permitting, it would be possible to further extend the coverage of EMMA with Limited Streamer Tubes [13]. This would enlarge the total instrumented area by 180 m² (60 modules, 3 m² each).

3.2.1. Drift chamber

The drift chambers, referred to as planks, operate in the proportional mode at the anode voltage of approximately 6 kV. Instead of the original gas

mixture of Ar(85.5%):CH₄(8.5%):CO₂(6%) we chose to use an Ar(92%):CO₂(8%) mixture to avoid the use of methane gas in the mine environment even if that slightly reduces the performance.

Each plank consists of seven position-sensitive drift chambers (365 × 20 cm², 20mm thick) arranged in lengthwise half-overlapping groups of 3+4 (the area of 2.9 m² each). The gas volume of one drift chamber is 16×200×3650 mm³ (height×width×length), or 11.68 l. The total gas volume for the seven chambers is ≈80 l. The cross-section of a plank are shown in Fig.2 [14].

The absolute position calibration in the delay-line direction was performed on the surface using a ²²Na source and employing cosmic muons and muon tracking. The muon detection efficiency was carried out using tracking to compare the numbers of fired chambers to those not detecting muons even if the track is passing through the given chamber. This takes into account both the geometry and the air pressure changes.

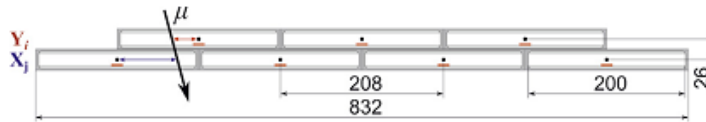


Figure 2 – Schematic cross-section of a plank. The black dot is the anode wire and the red square is the delay line (copper) used for longitudinal position determination. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Plastic scintillation detectors

In addition to the drift chambers EMMA employs plastic scintillation detectors. These detectors were designed for EMMA and were manufactured by INR/RAS, Moscow. The 3 cm thick plastic scintillation pixels, equipped with Silicon Photomultipliers have an area of 122×122 mm². They are arranged into units with 16 pixels, called SC16, housed in a 1 mm thick metal shielding. The total active area of SC16 is 0.5×0.5 m². The electronic is placed above the scintillator surface, as shown in Fig.3. The total of 96 SC16 units was manufactured. Currently 72 SC16s are installed in EMMA providing 72×16=1152 individual detector channels covering the total area of 18 m². The technical details concerning SC16 are given in [11].

The efficiency calibrations of SC16s were carried out on the surface to benefit from the larger muon flux. The timing studies were performed using

two overlapping sets of SC16s placed in the middle and bottom levels in the Station G. In total, the test setup consisted of 128 + 384 = 512 pixels in two layers separated by the vertical gap of 1125 mm.

3.3 CORSIKA simulations

Figure 4 shows CORSIKA simulations [15] of the muon lateral density distribution for the primary CR with energies of 1, 3 and 10 PeV both for proton- and for iron-initiated air showers. Energy threshold of $E_{\mu} > 50$ GeV was applied reflecting the average absorption in the overburden. The figure reveals two important features relevant to EMMA: i) the primary energy translates to the muon density at the shower core and is practically independent on mass, and ii) the slope of muon density distribution differs for proton and iron-initiated showers. These two features provide the basis for the extraction of the energy and of the mass of the primary cosmic ray from the data [16].

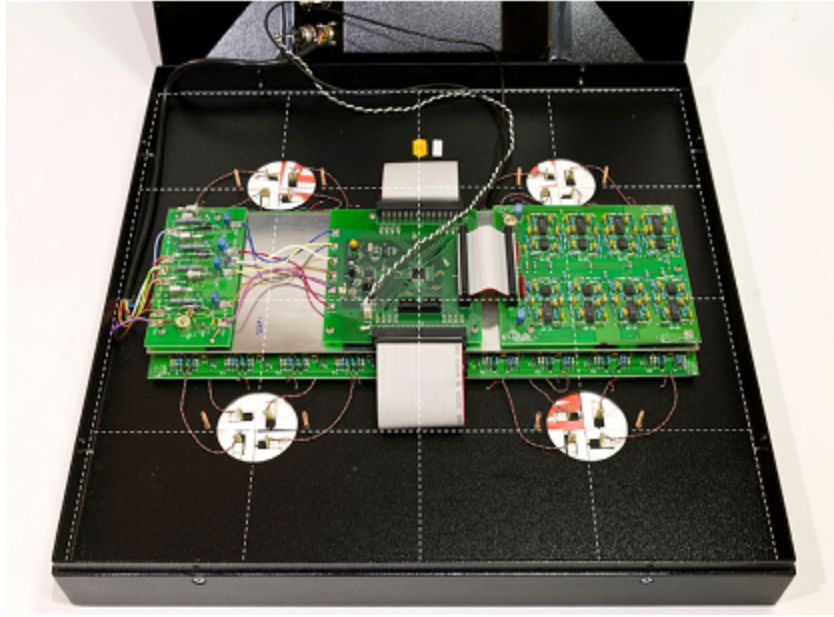


Figure 3 – SC16 electronics. The dashed white lines outline the areas of 16 individual pixels. The electronics is mounted above the scintillator plane.

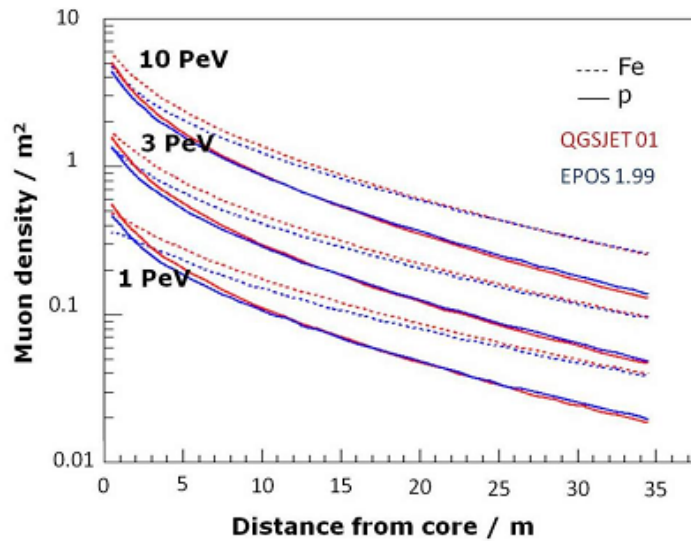


Figure 4 – Simulated lateral muon density distributions of high-energy muons ($E_{\mu} > 50$ GeV) of proton- and iron-induced air showers at 1, 3 and 10 PeV energies. CORSIKA+QGSJET 01 and CORSIKA+EPOS 1.99 models indicated by red and blue lines, respectively.

3.4 Significance of EMMA

The novel approach implemented by EMMA is to restrict the detection to the high-energy muonic component of EAS. It is achieved by locating the detector array underground at a shallow depth of about 75 meters (210 m.w.e), corresponding to the muon cutoff energy of about 45 – 50 GeV. If the

instrumentation of the constructed infrastructure is completed and the setup is operated in the full configuration for three years, EMMA would make a significant contribution towards solving of the long-standing puzzle of the presence of the knee in the energy spectrum of cosmic rays. This, in turn, may reveal further information on cosmic-ray sources

and acceleration mechanisms. The current understanding is that the acceleration can take place up to the knee energies in supernova shock fronts that could propagate thousands of years after the explosion. However, there should be also other mechanisms since the supernova shock front mechanism does not produce energies above the knee. Addressing these questions is relevant and important as they are among the major topics in present-day astrophysics.

The second important task of EMMA is to verify the alleged muon excess in EAS. This problem is extremely important because, if confirmed, it would force a substantial revision of the existing particle interaction models with serious repercussions in multiple fields of science relying on these models. For example, the results from Pierre Auger Observatory and Yakutsk EAS Array indicate that there is an excess of muons in extensive air showers compared with the numbers extracted from the most realistic theoretical models. On the other hand, Ice-Top and EAS-MSU did not find such excess. If the excessive production of muons in EAS would be confirmed by a methodologically different experiment such as EMMA, it would have important implications for the current particle interaction models.

The possible origin of the discrepancy may also be the difference in the energy of detected muons. While the majority of experiments reporting muon excess detect muons with energies around 1 GeV, experiments focusing on energies around 10 GeV, like the EAS-MSU experiment, do not find the excess. The muon energy cut-off at the location of EMMA underground arrays is even higher: 45 GeV. Because of that EMMA has an opportunity to confirm or disprove the existence of the energy dependence of the muon excess and clarify the origin of the effect itself.

C14 experiment

The beta decay of the long-lived radioactive ^{14}C is the main source of background for low-energy ($E < 300$ keV) neutrino measurements using high-purity liquid scintillation detectors [12]. The lowest ^{14}C concentration has been reported by the Borexino Collaboration for Pseudocumene (PC) amounting to $\sim 2 \times 10^{-18}$ [13]. There are three other published results for the concentration (for PXE and PC+Dodecane) with the highest being $(12.6 \pm 0.4) \times 10^{-18}$ [17][18][19]. Such low concentrations are currently below the sensitivity of the Atomic Mass Spectrometry [20].

The preferred solvent for the new generation of large neutrino detectors is LAB (Linear alkylbenzene). LAB, just like the other petrochemical products, is synthesized from the crude gas or oil extracted from old geological deposits where the remanences of the cosmogenic ^{14}C are expected to be very low. Therefore, if contamination during processing, transportation and storage can be avoided, it should be possible to manufacture LAB with a low concentration of the radiocarbon [21]. We intended to make systematic analysis of the samples of different origin and composition with the aim of finding concentrations smaller than 10^{-18} for use, for instance, by the SNO⁺ [8] and the JUNO Collaboration [9].

Future plans and possibilities

5.1 Giant liquid-based neutrino detectors

As mentioned before, the Pyhäsalmi mine has ideal conditions to host underground experiments of the next generation [22]. In fact, Pyhäsalmi was already selected as the prime site for the far detector of the LAGUNA-LBNO project and the feasibility for the construction in Finland of giant caverns, capable of containing 50 kiloton-size detectors in a single cave has been documented [23]. The plan was to produce a high-energy neutrino beam at CERN and send it over the distance of 2288 km to Finland [24]. However, following the new European strategy on particle physics, Fermilab took over from CERN accelerator-based neutrino physics and the LAGUNA-LBNO was replaced by the DUNE experiment [25].

The second of the LAGUNA detectors that has chosen the Pyhäsalmi mine as its preferred location is LENA (Low Energy Neutrino Astronomy) – a multi-purpose neutrino observatory employing 50 kilotons of liquid scintillator [26]. Unfortunately, LENA Collaboration failed to obtain support from the funding agencies. Instead, the majority of the neutrino scientists involved with the liquid scintillator technology have joined the Jiangmen Underground Neutrino Observatory (JUNO) – a medium-baseline reactor neutrino experiment, currently under construction in South China [7]. Nevertheless, it is conceivable that, in a few years, LENA or a similar project will be reconsidered because JUNO, located at a relatively shallow depth of 600 meters and at the distance of only 53 km from 10 high-power nuclear reactors, won't have the desired sensitivity to address the astroparticle goals of LENA.

5.2. Acoustic detection of neutrinos in the rock

As a legacy of the extended site investigation for LAGUNA-LBNO and decades of mining and exploration activities, there is a network of boreholes surrounding the ore body. These boreholes have a very well documented geological profile and are now available for scientific research. The area covers the volume of about 1 km³ reaching from the depth of around 1300 m down to 2500 m. The total length of the new boreholes is 3.5 km. It has been proposed [27] to deposit strings of microphones into the boreholes in a similar fashion it has been done or is going to be done by the ANTARES/AMADEUS [28] and the KM3NeT collaborations for the purpose of acoustic detection of particleshowers following interactions of ultra-high energy neutrinos. Performing this type of measurements in the rock has never been tried or

even proposed before. It is expected that since the density of the rock is three-times larger and the speed of sound is four-times larger, the amplitude of the generated bipolar pressure pulse in rock following the interaction with an ultra-high energy neutrino should be by an order of magnitude larger than in water. In addition, a higher density of rock also guarantees higher interaction rate for neutrinos while a longer attenuation length in rock reduces signal dissipation.

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References

- 1 Kampert K.H., Mostafa M.A., Zas E. et al. Multi-Messenger Physics With the Pierre Auger Observatory //Front. Astron. Space Sci. – 2019. – Vol. 6, No. 24. – P.6.
- 2 Apel W. D. et al. KASCADE-Grande Collaboration //Astroparticle Physics. – 2013. – Vol.47. – P.54.
- 3 Zhao Y., Yuan Q., Bi X.J., Zhu F.R. and Jia H.Y. Perspective of detecting very high energy gamma-ray emission from active galactic nuclei with Large High Altitude Air Shower Observatory (LHAASO) // Intern. J. Of Modern Physics D. – 2016. – Vol.25, Iss. 1. – No. 1650006.
- 4 Kalliokoski T., Bezrukov L., Enqvist T., Fynbo H., and Virkajärvi A. Advantages of locating LAGUNA in Pyhasalmi mine //Progress in Particle and Nuclear Physics – 2011. – Vol. 66, – Iss. 2. – P. 468–472.
- 5 Trzaska W.H. et al., Advantages of locating LAGUNA in Pyhäsalmi mine //Prog. Part. Nucl. Phys. – 2011. – Vol. 66. – P. 463–467.
- 6 Trzaska W.H., Site selection for the new generation of giant neutrino detectors //J. Phys. Conf. Ser. – 2012. – Vol. 375. – P. 042060.
- 7 Alimonti G. et al. Measurement of the C-14 abundance in a low-background liquid scintillator //Phys. Lett., B. – 1998. – Vol. 422. – P. 349–358.
- 8 Chen Mark C. The SNO+ Experiment. In Proceedings, 34th International Conference on High Energy Physics (ICHEP 2008): Philadelphia, Pennsylvania, July 30-August 5, 2008.
- 9 An F. et al. Neutrino Physics with JUNO //J. Phys. G. – 2016. – Vol. 43(3). – No. 030401.
- 10 P. Aarnio and The DELPHI Collaboration, The DELPHI detector at LEP //Nucl. Inst. Meth.in Phys.Res.A. – 1991. – Vol. 303. – P. 233-276.
- 11 Akhrameev E.V., et al., Multi-pixel Geiger-mode avalanche photodiode and wavelength-shifting fibre-optics readout of plastic scintillator counters for the EMMA underground experiment //Nucl.Inst. Meth.in Phys.Res.A. – 2009. – Vol. 610, – Iss. 1. – P. 419-422.
- 12 Bandac, et al., Calculation of total muon flux observed by Muon Monitor experiment //J. Phys.Conf.Ser. – 2017. – Vol. 934. – No. 012019.
- 13 Antoni T., et al. A large area limited streamer tube detector for the air shower experiment KASCADE-Grande //Nucl.Inst. Meth.in Phys.Res.A. – 2004. – Vol. 533. – P. 387-403.
- 14 Kuusiniemi P., Bezrukov L., Dzaparova I., Enqvist T., Yanin A. Possibilities for Underground Physics in the Pyhäsalmi mine //Astroparticle Physics. – 2018. – Vol. 102, – P. 67-76.
- 15 Heck D., Capdevielle J.N., Schatz G. and Throuw T., Corsika: A Monte Carlo Code to Simulate Extensive Air Showers // Report FZKA 6019. – 1998.
- 16 Kuusiniemi P., Bezrukov L., Enqvist T. and Trzaska W.H., Underground cosmic-ray experiment EMMA //J. Phys.: Conf. Ser. – 2013. – Vol. 409. – No. 012067.
- 17 Back H.O. et al. Study of phenylxylylethane (PXE) as scintillator for low energy neutrino experiments //Nucl.Instrum.Meth. A. – 2008. – Vol.585. – P.48–60.
- 18 Keefer G. Laboratory Studies of Lead Removal from Liquid Scintillator in Preparation for KamLAND’s Low Background Phase //AIP Conf. Proc. –2011. – Vol. 1338. – P. 175–178.

- 19 Buck C. et al. Measuring the $(14)\text{C}$ isotope concentration in a liquid organicscintillator at a small-volume setup // *Instrum. Exp. Tech.* – 2012. – Vol. 55. – P. 34–37.
- 20 Accelerator mass spectrometry (AMS) dating. <https://www.radiocarbon.com/accelerator-mass-spectrometry.htm>.
- 21 Bonvicini G. et al. The chemical history of 14C in deep oilfields // <https://cds.cern.ch/record/636433/files/0308025.pdf>. – 2003. –16 p.
- 22 Trzaska W.H. et al., Advantages of locating LAGUNA in Pyhäsalmi mine // *Prog. Part. Nucl. Phys.* – 2011. – Vol.66. – P.463–467.
- 23 Trzaska W.H. Site selection for the new generation of giant neutrino detectors // *J. Phys. Conf. Ser.* – 2012. – Vol. 375. – No. 042060.
- 24 Galymov V..The LAGUNA-LBNO neutrino observatory in Europe // *Nucl. Part. Phys. Proc.* – 2016. – Vol. 273-275. – P.1854–1860.
- 25 <http://www.dunescience.org/>
- 26 Wurm M. et al. The next-generation liquid-scintillator neutrino observatory LENA // *Astropart. Phys.* – 2012. – Vol. 35. – P. 685–732.
- 27 Trzaska W.H. et al. Acoustic detection of neutrinos in bedrock // *EPJ Web Conf.* – 2019. –Vol. 216, No 04009. – P. 6.
- 28 Aguilar J.A. et al. AMADEUS – The Acoustic Neutrino Detection Test System of the ANTARES Deep-Sea Neutrino Telescope // *Nucl.Instrum.Meth. A.* – 2011. – Vol. 626-627. – P.128–143.

References

- 1 K.H. Kampert et al. *Front. Astron. Space Sci.*, 6 (24) (2019).
- 2 W.D. Apel et al. *Astroparticle Physics*, 47, 54 (2013).
- 3 Y. Zhao et al. *Intern. J. Of Modern Physics D*, 25 (1), 1650006 (2016).
- 4 T. Kallioikoski et al. *Prog. Part. Nucl. Phys.*, 66, 468–472 (2011).
- 5 W.H. Trzaska et al., *Prog. Part. Nucl. Phys.*, 66, 463–467, (2011).
- 6 W.H. Trzaska et al., *J. Phys. Conf. Ser.*, 375, 042060 (2012).
- 7 G. Alimonti et al., *Phys. Lett.*, B422, 349–358 (1998).
- 8 C. Che. Mark et al., 34th Intern. Conf. on High Energy Physics (ICHEP 2008), Philadelphia, Pennsylvania, July 30-August 5 (2008).
- 9 An. Fengpeng et al., *J. Phys.*, G43 (3), 030401 (2016).
- 10 P. Aarnio and the DELPHICollaboration, *Nucl.Inst. Meth.in Phys.Res. A303*, 233 (1991).
- 11 E.V. Akhrameev et al., *Nucl. Inst. Meth. in Phys.Res. A610*, 419 (2009).
- 12 Bandac et al., *J. Phys.Conf.Ser.* 934, 012019 (2017).
- 13 T. Antoni et al., *Nucl.Inst. Meth.in Phys.Res. A533*, 387 (2004).
- 14 P. Kuusiniemi et al., *Astroparticle Physics*, 102, 67–76 (2018).
- 15 D. Heck et al., *Report FZKA*, 6019 (1998).
- 16 P. Kuusiniemi et al., *J. Phys. Conf. Ser.*, 409, 012067 (2013).
- 17 H.O. Back et al., *Nucl. Instrum. Meth.*, A585, 48–60 (2008).
- 18 G. Keefer., *AIP Conf. Proc.*, 1338, 175–178 (2011).
- 19 C. Buck et al., *Instrum. Exp. Tech.*, 55, 34–37 (2012).
- 20 Accelerator mass spectrometry (AMS) dating. <https://www.radiocarbon.com/accelerator-mass-spectrometry.htm>.
- 21 G. Bonvicini et al., <https://arxiv.org/abs/hep-ex/0308025v2> (2003).
- 22 W.H. Trzaska et al., *Prog. Part. Nucl. Phys.*, 66, 463–467 (2011).
- 23 W.H. Trzaska et al., *J. Phys. Conf. Ser.*, 375, 042060 (2012).
- 24 Vyacheslav Galymov et al., *Nucl. Part. Phys. Proc.*, 273-275, 1854–1860 (2016).
- 25 Dune. <http://www.dunescience.org/>. Accessed: 2018-09-30.
- 26 M. Wurm et al., *Astropart. Phys.*, 35, 685–732 (2012).
- 27 W.H. Trzaska et al., *EPJ Web Conf.*, 216, 04009 (2019).
- 28 J.A. Aguilar et al., *Nucl. Instrum.Meth.*, A626-627, 128–143 (2011).