NUCLEAR EXPERIMENTAL TECHNIQUE

A Passive Shield for the RED-100 Neutrino Detector

D. Yu. Akimov^a, I. S. Aleksandrov^{a,b}, V. A. Belov^{a,c}, A. I. Bolozdynya^{a,*}, Yu. V. Efremenko^d,
A. V. Etenko^{a,e}, A. V. Galavanov^{a,f}, D. V. Gouss^a, Yu. V. Gusakov^{a,f}, Dj. E. Kdib^a, A. V. Khromov^a,
A. M. Kononov^{a,c}, V. N. Kornoukhov^{a,g}, A. G. Kovalenko^{a,c}, A. A. Kozlov^a, E. S. Kozlova^{a,c},
A. V. Kumpan^a, A. V. Lukyashin^{a,h}, A. V. Pinchuk^a, O. E. Razuvaeva^{a,c}, D. G. Rudik^a, A. V. Shakirov^a,
G. E. Simakov^{a,c}, V. V. Sosnovtsev^a, and A. A. Vasin^a

^a National Research Nuclear University MEPhI (Moscow Engineering Physics Institute),
Moscow, 115409 Russia

^b National Research Tomsk Polytechnic University,
Tomsk, Russia

^c Alikhanov Institute for Theoretical and Experimental Physics, Kurchatov Institute National Research Center,
Moscow, Russia

^d Department of Physics and Astronomy, University of Tennessee,
Knoxville, Tennessee, USA

^e Kurchatov Institute National Research Center, Moscow, Russia

^f Joint Institute for Nuclear Research, Dubna, Moscow oblast, Russia

^g Institute for Nuclear Research, Russian Academy of Sciences,
Moscow, Russia

^h Moscow State University, Moscow, Russia

*e-mail: aibolozdynya@mephi.ru

Received October 29, 2020; revised November 6, 2020; accepted November 9, 2020

Abstract—A combined passive shield of the RED-100 two-phase emission neutrino detector has been developed and built for suppressing the background of external γ rays and neutrons. The shield is composed of a 5-cm-thick copper layer (the inner layer is adjacent to the detector) and a water layer with a total thickness of approximately 70 cm (including the water inside the copper shield). The Monte Carlo simulation of the shielding efficiency has been performed. The obtained attenuation factor of the copper shield for the γ -ray background has been experimentally verified in a laboratory test using a NaI(Tl) scintillator detector. The γ -ray background rejection factor of the full shield has also been calculated.

DOI: 10.1134/S0020441221020093

INTRODUCTION

Coherent elastic neutrino scattering off an atomic nucleus (CEvNS) was predicted within the Standard Model almost simultaneously by American [1] and Soviet [2] scientists in 1974. Instead of interacting with individual nucleons of a nucleus, a neutrino interacts in this process with the entire nucleus and transfers a part of its kinetic energy to it. A recoil nucleus (more precisely, a recoil atom) with a very weak signature, i.e., kinetic energy in the kiloelectronvolt and sub-kiloelectronvolt ranges, is the sole detectable product of this reaction. For this reason, the CEvNS process was discovered by the COHERENT collaboration on Cs and I nuclei only in 2017, although its cross section is large (compared to other neutrino interactions) [3].

The COHERENT collaboration reported observation of this process on an argon nucleus quite recently [4]. These experiments conducted at the Oak Ridge

National Laboratory (United States) revealed CEvNS events caused by a mixture of three types of high-energy neutrinos from a pulsed proton source, which were produced in decays of π^+ mesons at rest. Investigation of the CEvNS process using reactor neutrinos is a matter of particular interest, since a nuclear reactor produces neutrinos of a specific type (electron antineutrinos) and, compared to an accelerator experiment, makes it possible to expand the energy range in studying the CEvNS process towards the region of lower neutrino energies, thus providing almost complete scattering coherence. This is important in verifying the theoretically predicted dependence of the CEvNS cross section on the neutrino energy and on the number of neutrons in a nucleus.

Observing reactor antineutrinos via CEvNS is a difficult task that requires the detection of significantly weaker signals than in an experiment at an accelerator, against a background of cosmic muons,

fast neutrons, and environmental γ rays. Despite the existing difficulties, several experimental collaborations are actively working in this direction: CONUS, TEXONO, vGeN [5–7], which use high-purity germanium detectors; MINER, RICOCHET, v-cleus [8–10], which use bolometers at temperatures of several tens of millikelvin; and CONNIE, which uses a low-noise charge-coupled device for particle identification [11].

Today, we are preparing an experiment to detect the CEvNS process on a Xe nucleus using the RED-100 two-phase emission detector containing more than 100 kg of xenon in its sensitive part. The two-phase emission method for particle detection was proposed by Soviet scientists 50 years ago in [12]. Detectors of this type are used in modern experiments on the direct search for dark matter and on the neutrino detection in underground laboratories [13–17]. This method makes it possible to measure ionization signals with an ultra-small intensity, down to the intensity of the signals produced by single ionization electrons. This exactly corresponds to the task of observing the CEvNS process [18]. The use of heavy xenon nuclei as a target is a matter of particular interest for studying the CEvNS process, since xenon has the heaviest atomic nucleus among substances from which detectors sensitive to sub-kiloelectronvolt energy release can be built. In addition, the CEvNS process on a xenon nucleus has the largest cross section.

The RED-100 detector [19] will be installed under the VVER-1000 reactor of the fourth power unit of the Kalinin nuclear power plant (KNPP) at a distance of 19 m from the reactor core. The thermal power of the reactor is 3 GW; the antineutrino flux at the detector site is $\sim 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$.

In this paper we describe the design of a passive shield for the RED-100 detector, the results of in the laboratory testing of a copper component of this shield, and the simulated efficiency of the full shield against the external γ -ray background. The shielding efficiency against a neutron background at the KNPP is not considered in this paper, since such a calculation requires initial experimental data on the neutron background at the planned location of the experiment.

Since we did not have the opportunity to test the ready-assembled complete shield prior to the transportation of the experimental setup to the KNPP, we measured the γ -ray background in the laboratory at the National Research Nuclear University MEPhI using a NaI(Tl) scintillator detector, the intrinsic γ -ray background of this detector, and the γ -ray background inside the copper shield. The Monte Carlo simulation of the measured external background was carried out and the concentrations of the main γ -ray sources, i.e., the U/Th decay chains and ^{40}K in the concrete of the laboratory floor were extracted from the obtained fit. Based on these results, we simulated the rejection of the γ -ray background by the copper shield and com-

pared the energy spectrum of the resulting model background to the spectrum measured inside the copper shield. The final efficiency of the full shield was obtained from the simulation after the water shield was added to the copper shield.

JUSTIFICATION FOR THE SELECTED DESIGN OF THE PASSIVE SHIELD FOR THE RED-100 DETECTOR

Our task was to create a compact, lightweight (due to the limited load on the floor in the KNPP premises), fireproof, and low-cost shield against external radiation background with the following main components:

- γ rays and neutrons from natural radioactive isotopes in the materials of the KNPP building and structures (the contribution of the radiation background from the reactor at the site of the experimental setup is not significant);
- neutrons generated by the interaction of cosmic muons with the materials of the KNPP building and structures.

As an ideal passive shield against the above sources, we could consider a large water tank (~ 10 m in diameter) filled with purified water, which is similar to the tanks used in modern experiments to search for dark matter in underground laboratories. However, taking the above limitations into account, we realize that it is impossible to place a water tank with a diameter more than 2 m in the KNPP premises. In this case, the thickness of the water layer between the walls of the detector and the tank turns out to be insufficient for the complete absorption of high-energy γ rays.

In this regard, we decided to place an additional 5-cm-thick shielding layer made of a high- Z material at the minimum distance from the detector body, which provided the minimum mass of the shield with the prescribed thickness. Copper and lead shields were considered and copper was selected owing to the following main arguments:

- the specific yield of neutron production per cosmic muon for lead is $(7.2 \pm 0.7) \times 10^{-5} \text{ g}^{-1} \text{ cm}^2$, which is more than 3 times higher than the corresponding value for copper, i.e., $(2.1 \pm 0.4) \times 10^{-5} \text{ g}^{-1} \text{ cm}^2$ [20];
- copper is a much cleaner material compared to lead in terms of the content of radioactive impurities.

A diagram of the passive shield for the RED-100 detector is shown in Fig. 1. The vessel 3 filled with water is a soft reinforced-plastic tank with a diameter of 2.2 m. It is located inside the octagonal (in a horizontal cross section) support frame 2, which is made of an AL-PS-6060-A aluminum structural profile with a cross section of $6 \times 6 \text{ cm}^2$. The RED-100 detector 5 and the surrounding copper shield 4 are fixed in place on a 0.6-m-high aluminum-profile pedestal at

Fig. 1. The radiation shield of the RED-100 detector: (1) Dewar vessel of the thermosiphon, (2) support frame, (3) water tank, (4) copper shield, and (5) the RED-100 detector.

the center of the tank (see Fig. 1 on the right). The total detector-to-floor distance is 0.87 m.

The copper shield is assembled from bars with dimensions of $0.05 \times 0.05 \times 0.85$ m, which are connected by steel pins. The outer dimensions of the copper shield are $0.9 \times 0.9 \times 1.6$ m. The system for detector cooling and thermal stabilization is based on thermosiphon 1 (for detailed description, see [21]) and is placed outside the water shield. The thermosiphon cooling pipes pass inside a bellows metal hose that is connected to the central flange of the detector on the top cover of the detector cryostat.

Metal bellows hoses (not shown in Fig. 1) are connected to three other flanges and are used to fill the detector with xenon, supply high-voltage power to the detector, and for signal readout using coaxial cables. All of the above lines of communication with the detector pass through a rectangular 0.45×0.40 m window in the upper part of the copper shield. Taking the square cross-section of the copper shield into account, the average distance between the copper shield and the wall of the water tank is approximately 0.6 m, and the average distance between the copper shield and the detector wall is approximately 0.1 m.

THE γ -RAY BACKGROUND MEASUREMENT AND SIMULATION

Evaluation of the efficiency of the passive shield against an external γ -ray background requires knowledge of the energy spectrum of this background in its site. According to the measurements carried out by the DANNs group in the KNPP room located above the RED-100 detector site in [22], the γ -background spectrum and intensity are not much different from the corresponding characteristics of the natural back-

ground produced by γ -ray sources from the U/Th decay chains and ^{40}K in concrete. In this regard, the γ -ray background was measured outside and inside the completely assembled copper shield in the laboratory of the National Research Nuclear University MEPhI in order to determine the efficiency of the passive shield against the external γ background.

The measurements were carried out using a scintillation detector based on a NaI(Tl) crystal in the form of a cylinder with a diameter of 150 mm and a height of 100 mm. The detector signals were amplified and shaped using an ORTEC 570 spectroscopy amplifier and then were fed to an ORTEC MCA-927 dual-input multichannel analyzer controlled using the MAESTRO software [23]. This software allowed us to determine the live time of measurements, which made it possible to compare the γ -background intensity outside and inside the shield.

Before the measurements, the spectrometric channel was calibrated using ^{22}Na (511 and 1275 keV), ^{40}K (1461 keV), and ^{232}Th (with a well-defined peak at 2615 keV from ^{208}Tl) γ -ray sources. A 1-cm-thick Teflon plate absorbed β particles emitted by this source simultaneously with γ rays. The NaI(Tl) detector was placed inside a thick passive combined lead–copper shield (Fig. 2) during the calibration measurements with the low-intensity ^{232}Th source and when measuring the intrinsic background of the detector. This shield suppressed the external γ -ray background by several orders of magnitude. The equipment was warmed up before the measurements for 3–5 h to achieve stable characteristics of the spectrometric channel.

The results of the energy calibration of the NaI(Tl) detector and the verification of the linearity of its energy scale are shown in Fig. 3a. The graph shows

Fig. 2. The combined lead–copper shield for measuring the intrinsic background of the NaI(Tl) scintillator detector: (1) copper, (2) NaI(Tl) detector, and (3) lead.

Fig. 3. The results of the calibration of the spectrometric channel for the NaI(Tl) detector: (a) linearity of the energy scale and (b) dependence of the energy resolution on the γ -ray energy. The measurement errors (if not shown) were less than the dot size.

that the energy scale is linear over the entire measurement range of the γ -ray background (see below). Figure 3b shows the energy resolution of the detector as a function of the γ -ray energy, which was approximated by the formula:

$$\frac{\sigma}{E} = \sqrt{a^2 + \frac{b^2}{E}},$$

where E is the γ -ray energy; σ is the standard energy deviation; and a and b are the parameters whose values are shown in the inset of Fig. 3b. This energy dependence of the energy resolution of the detector was taken into account in the Monte Carlo simulation of the γ -ray background.

The measured energy distribution of radiation background events in the laboratory in the energy range of 0.4–5.0 MeV is shown as a shaded histogram in Fig. 4. The detector was placed on the laboratory floor without any shield. This distribution was approximated by components from individual γ -ray sources by the Monte Carlo simulation using the GEANT4 package [24, 25]. The radionuclides in the ^{238}U , ^{232}Th , and ^{40}K decay chains were specified in the model experiment. The concentrations of these elements were varied as free parameters and the intermediate

decay products in these chains were assumed to be in equilibrium.

The radionuclides of the model were uniformly distributed over the concrete floor (the main source of the γ background in the laboratory) with an area of 6×6 m and a thickness of 0.5 m. This thickness has been selected, since, as shown in the simulation, the γ -ray flux from deeper layers can be neglected. As was the case during the measurements, the detector in the model was located on the floor. In addition to the contribution of γ rays from the above radionuclides, the detector background measured separately inside the lead–copper shield was taken into account in the approximation. This background included the intrinsic γ and β backgrounds of the detector and the low-energy part of the energy spectrum of cosmic muons.

The simulation showed that the experimental background spectrum was approximated well by the sum histogram 2 if the floor material contained ^{238}U , ^{232}Th , and ^{40}K with concentrations of 44 ± 1 , 21 ± 1 , and 203 ± 1 Bq/kg, respectively. The background components from these radionuclides are presented in Fig. 4 with histograms 4, 5, and 3, respectively. The obtained U/Th and K concentrations are typical of soil and concrete [22, 26, 27].

Fig. 4. (1) The measured radiation background in the laboratory room and (2) its model approximation by the contribution made by (3) ^{40}K , (4) ^{238}U , (5) ^{232}Th isotopes, including also (6) the intrinsic background of the NaI(Tl) detector activated by cosmic muons.

The massive support frame (2, Fig.1) was made of aluminum profile and was located in close proximity to the shield, could potentially contain high contribute to the γ -background due to radionuclide impurities. In order to check this hypothesis, a 52-g sample of an aluminum profile was sent to the underground Baksan Neutrino Observatory for radioactivity measurements with an ultra-low-background HPGe detector [28]. These measurements showed that the contribution to the γ -background from the support-frame material was small enough and can be neglected when simulating the background.

The measured energy distribution of radiation background events inside the completely assembled copper shield is shown as a shaded histogram in Fig. 5. The model γ background inside shield 2 was obtained from the above concentrations of ^{238}U , ^{232}Th , and ^{40}K isotopes in a concrete floor. The resulting model background 4 was determined as the sum of the γ -ray background 2 and the background 3 that was the intrinsic background of the NaI(Tl) detector, which was measured inside the lead-copper shield, and the background from cosmic muons. Figure 5 demonstrates good agreement between the values and shapes of the experimental and model radiation-background spectra inside the copper shield.

The slight excess of the experimental background over the model background can, most likely, be attributed to the unaccounted contribution of radionuclide sources of the γ -ray background in other places of the laboratory, as well as to the possible pres-

ence of some gaps between the copper bars of the shield. This stage of the study demonstrated that the created mathematical model of the copper shield and the distribution of sources in the laboratory are correct.

EVALUATION OF THE EFFICIENCY OF THE FULL SHIELD

The last step in this study was to simulate the completely assembled radiation shield (see Fig. 1) that included water and copper. The locations of radionuclide γ -ray sources in the concrete floor of the laboratory and their concentrations were specified in the same manner as described above. The γ -background spectrum on the surface of the RED-100 detector body (averaged over its surface) was obtained (Fig. 6) by simulation of the detector without the shield (histogram 1), with the water shield (histogram 2), and with the full shield, including the water and the copper (histogram 3). The simulation showed that the water shield without the copper significantly reduces (by approximately 50 times) the integral γ -ray flux and softens the γ -ray energy spectrum. A 5-cm-thick copper shield provides an additional decrease in the γ -ray flux by 10–13 times. The cumulative effect of the γ -background suppression by the passive shield made of water and copper is 500–1000, depending on the γ -ray energy.

Fig. 5. The radiation background inside the copper shield: (1) measured background, (2) model γ -ray background, (3) intrinsic background of the NaI(Tl) detector and the background from cosmic muons, and (4) the sum of the components (2) and (3).

CONCLUSIONS

A combined water–copper passive shield of the RED-100 two-phase emission xenon detector has been designed and produced for investigation of the CEvNS process at the KNPP. The shield meets the size and weight restrictions in the KNPP premises. The efficiency of γ -ray background rejection by the shield was simulated by the Monte Carlo method using the GEANT4 package. The developed model was verified by comparing the measured distribution

of signals from the NaI(Tl) scintillator detector enclosed in the copper shield to the model distribution. The obtained in a such way efficiency of γ -ray background rejection by the water–copper passive shield was 500–1000, depending on the γ -ray energy.

ACKNOWLEDGMENTS

We are grateful to Yu.M. Gavriluk, V.V. Kazalov, and V.V. Kuz'minov measurements of radiation-shield samples at the Baksan Neutrino Observatory of the Institute for Nuclear Research.

FUNDING

We express our gratitude to JSC Science and Innovations (Scientific Division of the Rosatom State Corporation), the Russian Science Foundation (contract no. 18-12-00135 dated April 12, 2018) for the cooperation and support in carrying out the experiment at the Kalinin NPP, the Competitiveness Enhancement Program of National Research Nuclear University MEPhI (contract no. 02.a03.21.0005 dated August 27, 2013.), and the Ministry of Science and Higher Education of the Russian Federation (Fundamental Properties of Elementary Particles and Cosmology Project no. 0723-2020-0041).

REFERENCES

1. Freedman, D.Z., *Phys. Rev. D: Part. Fields*, 1974, vol. 9, p. 1389.
<https://doi.org/10.1103/PhysRevD.9.1389>

Fig. 6. The model γ -ray background (1) outside and (2, 3) inside the passive shield, i.e., the water tank on the outside of the RED-100 detector cryostat (2) without and (3) with the copper shield being used.

2. Kopeliovich, V.B. and Frankfurt, L.L., *JETP Lett.*, 1974, vol. 19, p. 145.
3. COHERENT Collab., Akimov, D., et al., *Science*, 2017, vol. 357, no. 6356, p. 1123.
<https://doi.org/10.1126/science.aao0990>
4. COHERENT Collab., Akimov, D., et al., First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon, 2020. arXiv:2003.10630.
5. Hakenmüller, J., Buck, C., Fülber, K., Heusser, G., Klages, T., Lindner, M., Lücke, A., Maneschg, W., Reginatto, M., Rink, T., Schierhuber, T., Solasse, D., Strecker, H., Wink, R., Zbošil, M., and Zimbal, A., *Eur. Phys. J. C*, 2019, vol. 79, p. 699.
<https://doi.org/10.1140/epjc/s10052-019-7160-2>
6. Kerman, S., Sharma, V., Deniz, M., Wong, H.T., Chen, J.-W., Li, H.B., Lin, S.T., Liu, C.-P., and Yue, Q., *Phys. Rev. D*, 2016, vol. 93, p. 113006.
<https://doi.org/10.1103/PhysRevD.93.113006>
7. Belov, V., Brudanin, V., Egorov, V., Filosofov, D., Fomina, M., Gurov, Y., Korotkova, L., Lubashevskiy, A., Medvedev, D., and Pritula, R., *J. Instrum.*, 2015, vol. 10, p. 12011.
<https://doi.org/10.1088/1748-0221/10/12/P12011>
8. MINER Collab., Agnolet, G., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2017, vol. 853, p. 53.
<https://doi.org/10.1016/j.nima.2017.02.024>
9. Billard, J., Carr, R., Dawson, J., Figueroa-Feliciano, E., Formaggio, J.A., Gascon, J., Heine, S.T., Jesus, M.De., Johnston, J., Lasserre, T., Leder, A., Palladino, K.J., Sibille, V., Vivier, M., and Winslow, L., *J. Phys. G: Nucl. Part. Phys.*, 2017, vol. 44, no. 10, p. 105101.
<https://doi.org/10.1088/1361-6471/aa83d0>
10. Strauss, R., Rothe, J., Angloher, G., Bento, A., Gütlein, A., Hauff, D., Kluck, H., Mancuso, M., Oberauer, L., Petricca, F., Pröbst, F., Schieck, J., Schöner, S., Seidel, W., and Stodolsky, L., *Eur. Phys. J. C*, 2017, vol. 77, article no. 506.
<https://doi.org/10.1140/epjc/s10052-017-5068-2>
11. CONNIE Collab., Aguilar-Arevalo, A., et al., *Phys. Rev. D*, 2019, vol. 100, p. 092005.
<https://doi.org/10.1103/PhysRevD.100.092005>
12. Dolgoshein, B.A., Lebedenko, V.N., and Rodionov, B.U., *JETP Lett.*, 1970, vol. 11, p. 351.
13. LUX Collab., Akerib, D.S., et al., *Phys. Rev. Lett.*, 2017, vol. 118, p. 021303.
<https://doi.org/10.1103/PhysRevLett.118.021303>
14. XENON Collab., Aprile, E., et al., *Phys. Rev. Lett.*, 2018, vol. 121, p. 111302.
<https://doi.org/10.1103/PhysRevLett.121.111302>
15. PandaX-II Collab., Cui, X., et al., *Phys. Rev. Lett.*, 2017, vol. 119, p. 181302.
<https://doi.org/10.1103/PhysRevLett.119.181302>
16. DarkSide Collab., Agnes, P., et al., *Phys. Rev. D*, 2018, vol. 98, p. 102006.
<https://doi.org/10.1103/PhysRevD.98.102006>
17. DUNE Collab., Cuesta, C., et al., Status of Proto-DUNE Dual Phase, 2019. ArXiv: 1910.10115.
18. Akimov, D.Yu., Belov, V.A., Bolozdynya, A.I., Efremenko, Yu.V., Konovalov, A.M., Kumpan, A.V., Rudik, D.G., Sosnovtsev, V.V., Khromov, A.V., and Shakhov, A.V., *Phys.-Usp.*, 2019, vol. 62, no. 2, p. 166.
<https://doi.org/10.3367/UFNe.2018.05.038356>
19. RED-100 Collab., Akimov, D., et al., *J. Instrum.*, 2020, vol. 15, p. 02020.
<https://doi.org/10.1088/1748-0221/15/02/P02020>
20. Kneißl, R., Caldwell, A., Du, Q., Empl, A., Gooch, C., Liu, X., Majorovits, B., Palermo, M., and Schulz, O., *Astropart. Phys.*, 2019, vol. 111, p. 87.
<https://doi.org/10.1016/j.astropartphys.2019.03.006>
21. Anan'ev, V.V., Bolozdynya, A.I., Vlasik, K.F., Dmitrenko, V.V., Efremenko, Yu.V., Uteshev, Z.M., Sosnovtsev, V.V., Tolstukhin, I.A., Shakhov, A.V., Shafgullin, R.R., and Khromov, A.V., *Instrum. Exp. Tech.*, 2015, vol. 58, no. 4, p. 581.
<https://doi.org/10.1134/S0020441215030161>
22. Alekseev, I., Belov, V., Brudanin, V., Danilov, M., Egorov, V., Filosofov, D., Fomina, M., Hons, Z., Kazartsev, S., Kobayakin, A., Kuznetsov, A., Machikhiliyan, I., Medvedev, D., Nesterov, V., Olshevsky, A., et al., *J. Instrum.*, 2016, vol. 11, p. 11011.
<https://doi.org/10.1088/1748-0221/11/11/P11011>
23. <https://www.ortec-online.com/products/application-software/maestro-mca>.
24. GEANT4 Collab., Agostinelli, S., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2003, vol. 506, p. 250.
[https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
25. GEANT4 Collab., Allison, J., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2016, vol. 835, p. 186.
<https://doi.org/10.1016/j.nima.2016.06.125>
26. Kozlov, A. and Chernyak, D., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2018, vol. 903, p. 162.
<https://doi.org/10.1016/j.nima.2018.07.006>
27. Chazal, V., Brissot, R., Cavaignac, J.F., Chambon, B., Jesus, M.De., Drain, D., Giraud-Heraud, Y., Pastor, C., Stutz, A., and Vagneron, L., *Astropart. Phys.*, 1998, vol. 9, p. 163.
[https://doi.org/10.1016/S0927-6505\(98\)00012-7](https://doi.org/10.1016/S0927-6505(98)00012-7)
28. Busanov, O.A., Etezov, R.A., Gavriljuk, Yu.M., Gezhayev, A.M., Kazalov, V.V., Kornoukhov, V.N., Kuzminov, V.V., Moseev, P.S., Panasenkov, S.I., Ratkevich, S.S., and Yakimenko, S.P., *EPJ Web Conf.*, 2014, vol. 65, p. 03002.
<https://doi.org/10.1051/epjconf/20136503002>

Translated by N. Goryacheva