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A search for neutrino-induced inverse β-decay in ^{210}Bi spectrum

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We present results of ^{210}Bi β-spectrum analysis. A search for monoenergetic peak around the spectrum endpoint was performed. The presence of such peak would be the evidence of direct observation of inverse β-decay reaction, which can be caused, in particular, by capture of relic neutrino by the bismuth nucleus. The absence of statistically significant excess of such events allowed for setting of the upper limit on product of relic neutrino flux Φ_ν and capture cross-section σ_ν: $\sigma_\nu \cdot \Phi_\nu \leq 1.4 \cdot 10^{-12} s^{-1}$.

Keywords: cosmic neutrino background, inverse beta-decay, beta-spectrum.

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A possible method for observing relic neutrinos using the reverse β-decay on tritium nuclei was proposed by S. Weinberg and it is being considered in recent project PTOLEMY [1]. Optimistic forecasts for the detection of relic neutrinos are based on the assumption of their gravitational clustering effect in the vicinity of Earth [2]. As a result of the neutrino capture reaction a peak of monoenergetic electrons occurs at the endpoint region of β-spectrum Q_β. Consideration of a possibility of detecting the relic neutrinos capture by heavier nuclei, undergoing β-decay, is of fundamental interest. This paper outlines the endpoint energy region study of β-spectrum of ^{210}Bi isotope, which undergoes a first forbidden non-unique transition (to ground state ^{210}Po: $^{210}\mathrm{Bi}(1^-) \rightarrow {}^{210}\mathrm{Po}(0^+) + \tilde{\nu} + e^-$ ($Q_\beta = 1162.7$ keV, $T_{1/2} = 5.0d$). The ^{210}Bi nucleus has a number of unique characteristics, such as a strong difference in the shape of β-spectrum, allowed one and an abnormally long lifetime, and it has been widely studied since the 30s of the last century in a large number of experimental and theoretical works. In present paper, the search for the peak of monoenergetic electrons was carried out in (Q_β, $Q_\beta + 30$) keV energy range in order to include heavy sterile neutrinos with a mass of ~ 10 keV that are motivated candidates for the role of dark matter particles [3].

The isotope ^{210}Bi belongs to the natural chain of ^{238}U radioactive decay, being the product of ^{222}Rn gas decay and subsequent long-live lead isotope ^{210}Pb ($T_{1/2} = 22$ years). The carrier-free planar ^{210}Pb source was prepared by thermal oxidation with deposition on steel foil. The scheme of β-spectrum measurement was based on a simple geometry of β-spectrometer — „target-detector“. Si(Li) detector together with ^{210}Po-target was placed in a vacuum cryostat where it was cooled down to liquid nitrogen temperature. The signal from the detector was sent to charge-sensitive preamplifier, then to standard analog shaper and digitized by a 14-bit ADC [4]. Fig. 1 shows β-spectrum of ^{210}Bi obtained during 634 h of measurements. In the beginning of spectrum one may clearly see the spectrum of electrons and gamma-lines of the $^{210}\mathrm{Pb} \rightarrow {}^{210}\mathrm{Bi}$ decay.

The energy resolution of the Si(Li) detector, determined for conversion electrons with an energy of 30 keV, was 1.0 keV, the lower detection threshold was set to 5 keV. The data was accumulated in short 1-hour series to monitor the stability of the spectrometric path. The total of 10^8 electron events has been registered in total.

The measured β-spectrum of ^{210}Bi was expressed as

$$N(E) = \int_{E/mc^2+1}^{W_0} S(W) \cdot R(W, E) \cdot dW, \tag{1}$$

where $R(W, E)$ is normalized response function of the spectrometer obtained with Monte Carlo simulation of electrons flux with energy W; $S(W)$ is distribution of β-particles over energy that can be written as

$$S(W) = P \cdot W \cdot (W - W_0)^2 \cdot F(W, Z) \cdot C(W), \tag{2}$$

where P and W is momentum and full energy of electron, correspondingly; $W = T/m \cdot c^2 + 1$, where T is kinetic energy of electron; $W_0 = T_0/m \cdot c^2 + 1$ is the β-spectrum end-point energy; $F(W, Z)$ is Fermi function that takes into account interaction of the outgoing electron with the nucleus and atomic shell; $C(W)$ is nuclear form-factor that considers the effects of internuclear interactions.

The canonical Fermi function $F_0(W, Z)$, calculated initially in the point-like nucleus approximation, has been modified to include additional corrections:

$$F(W, Z) = F_0(W, Z) \cdot L_0(W, Z) \cdot M(W, Z) \cdot S(W, Z) \cdot G_\beta(W), \tag{3}$$

where Z is daughter nucleus charge, $L_0(W, Z)$ and $M(W, Z)$ is corrections for finite nucleus size (electromagnetic and weak interaction), $S(W, Z)$ is correction for atomic shell screening, $G_\beta(W)$ is radiative correction.

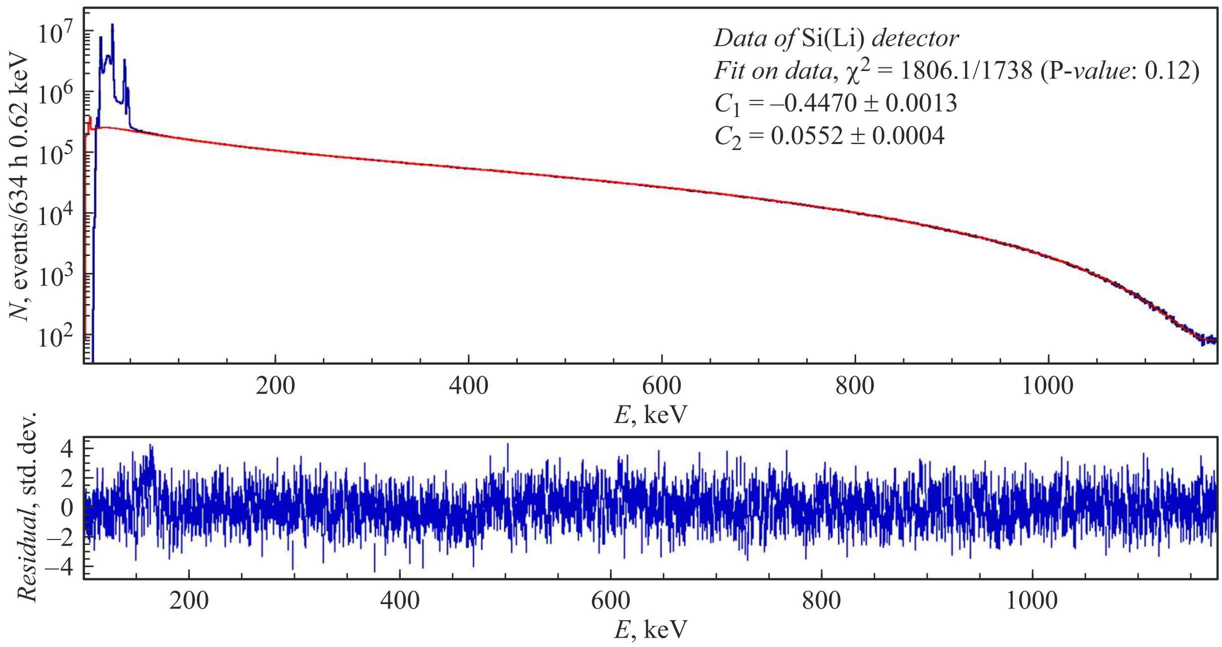

Figure 1. Spectrum of ^{210}Pb source measured by Si(Li) detector in 634 h.

The nuclear form-factor $C(W)$ was described using two parameters C_1 and C_2:

$$C(W) = 1 + C_1 \cdot W + C_2 \cdot W^2. \quad (4)$$

When modeling the response function, a homogeneous distribution of the electron's origin point inside the source and an isotropic angular distribution of the electron's momentum direction were assumed. GEANT 4.10.04 software with the standard electromagnetic interaction package G4Em Standard Physics Option4 was used for modeling. When fitting the measured spectrum, 6 parameters were varied: general normalization coefficient, slope of the calibration line, form-factor parameters C_1 and C_2 and two additional parameters of the spectrometer response function.

Fitting was performed in the energy range of 120−1175 keV with linear approximation of background. As a result, minimum of $\chi^2/NDF = 1806.1/1738$ was obtained, corresponding to significance level of $P = 0.12$ and form-factor parameters $C_1 = -0.4470 \pm 0.0013$ and $C_2 = 0.0552 \pm 0.0004$ [4].

In order to search for a peak near the end-point energy, a model of the experimental β-spectrum (1) has been supplemented with two parameters: E_{NC} and N_{NC}. Parameter E_{NC} that is equivalent to the energy of monoenergetic electron, when the peak was searched, fixed its position, whereas N_{NC} parameter was returned as an amplitude (number of events in the peak). β-spectrum was fitted similarly to the above procedure with the shape of spectrum (1), the parameters of the form-factor remained free, and the range of fitting was extended to 120−1200 keV. The most probable values of parameter N_{NC} were obtained within the energy range of 1162−1192 keV, which corresponds to the 0−30 keV interval of neutrino masses, with a spacing of 0.5 keV. No N_{NC} values deviating from zero value by more than 3 standard deviations were detected, indicating the absence of statistically significant peaks. For each value of N_{NC} the upper limit N_{90} was calculated by a number of neutrino capture events for the 90% confidence level, taking into account only positive part of the area of distribution function $f(N_{\text{NC}})$ (Fig. 2).

Fig. 3 shows the expected additional contribution to the measured spectrum at electron energy that is close to the end-point one $E_{\text{NC}} = 1162$ keV ($m_\nu \approx 0$). This corresponds to 790 events, which is 10 times more than the established upper limit at this energy.

The expected number of neutrino captures N_{NC} may be expressed as

$$N_{\text{NC}} = \sigma_\nu \cdot \Phi_\nu \cdot I \cdot t \cdot \tau, \quad (5)$$

where σ_ν is cross-section of neutrino capture reaction, Φ_ν is relic neutrino flux t is exposure, I is Si(Li) detector ^{210}Bi count rate that is defined by the long-live ^{210}Pb decay rate, and τ is lifetime of ^{210}Bi nucleus.

Based on condition that $N_{\text{NC}} < N_{90}(m_\nu)$, upper limits can be obtained for a product of interaction cross-section and the neutrino flux for different neutrino masses. In particular, the absence of peak in β-spectrum with the energy that is equal to the end-point one ($m_\nu \approx 0$, $N_{90} = 79$) results in limitation for product $\sigma_\nu \cdot \Phi_\nu \leq 1.4 \cdot 10^{-12}\,\text{s}^{-1}$.

Assuming that relic neutrinos with a concentration of 330 cm^{-3} move with non-relativistic velocities of dark matter particles ~ 300 km/s, we can obtain an upper limit for the interaction cross-section of relic neutrinos with ^{210}Bi nuclei: $\sigma_{\text{CNB}} \leq 1.4 \cdot 10^{-22}\,\text{cm}^2$. The upper limit for the mass of the heaviest neutrino state from the Planck

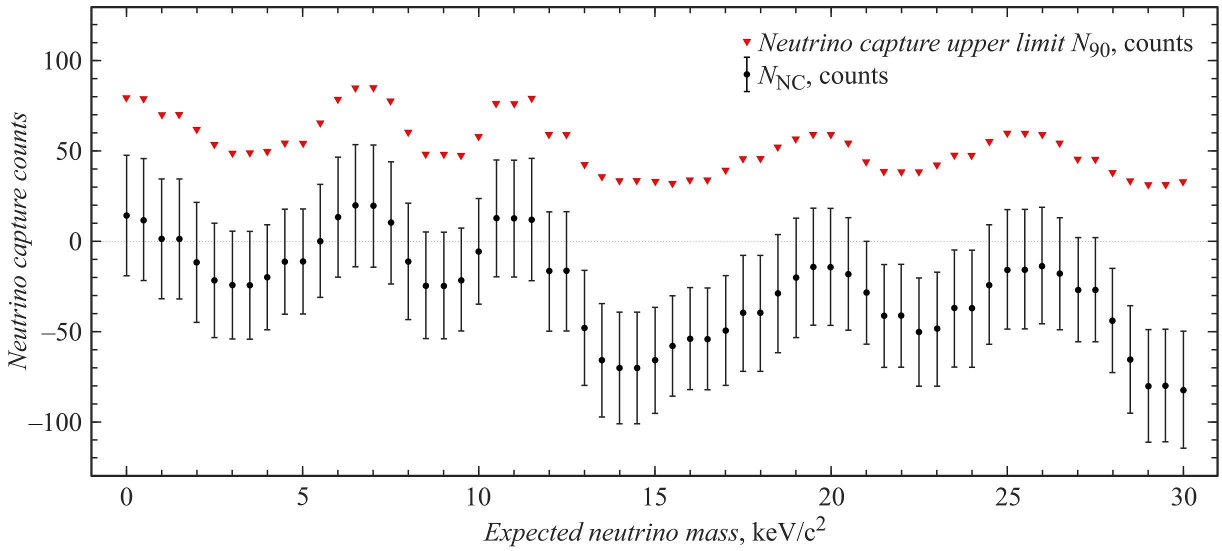

Figure 2. The most probable values N_{NC} and the corresponding upper limits N_{90} for various values of neutrino mass.

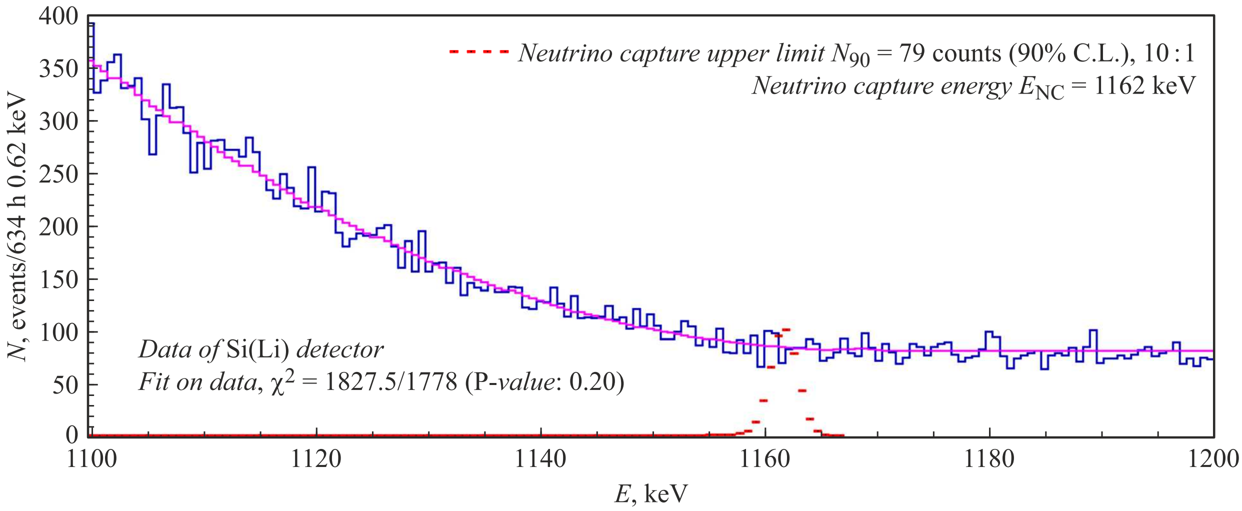

Figure 3. Measured spectrum in the interval 1100−1200 keV and detector response function at the energy level of E_{NC} = 1162 keV.

telescope data and the values of the oscillation parameters is 65 meV [5,6]. If we assume that all dark matter with density of 0.3 GeV/cm^3 consists of such neutrinos, the upper limit for the neutrino capture cross-section turns out to be more stringent: $\sigma_{DM} \leq 1.0 \cdot 10^{-29}$ cm^2 [7].

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.G. Betti, M. Biasotti, A. Bosca, F. Calle, N. Canci, G. Cavoto, C. Chang, A.G. Cocco, A.P. Colijn, J. Conrad, N. D'Ambrosio, N. De Groot, P.F. de Salas, M. Faverzani, A. Ferella, E. Ferri, P. Garcia-Abia, I. García-Cortés, G. Garcia Gomez-Tejedor, S. Gariazzo, F. Gatti, C. Gentile, A. Giachero, J.E. Gudmundsson, Y. Hochberg, Y. Kahn, A. Kievsky, M. Lisanti, C. Mancini-Terracciano, G. Mangano, L.E. Marcucci, C. Mariani, J. Martínez, M. Messina, A. Molinero-Vela, E. Monticone, A. Moroño, A. Nucciotti, F. Pandolfi, S. Parlati, S. Pastor, J. Pedrós, C. Pérez de los Heros, O. Pisanti, A.D. Polosa, A. Puiu, I. Rago, Y. Raitses, M. Rajteri, N. Rossi, I. Rucandio, R. Santorelli, K. Schaeffner, C.G. Tully, M. Viviani, F. Zhao, K.M. Zurek. J. Cosmology and Astroparticle Phys., 07, (2019).
DOI: 10.1088/1475 7516/2019/07/047

[2] J.-C. Peng, G. Baym. Phys. Rev. D, **106** (6), (2022). DOI: 10.1103/PhysRevD.106.063018

[3] R. Adhikari, M. Agostini, N. Anh Ky, T. Araki, M. Archidiacono, M. Bahr, J. Baur, J. Behrens, F. Bezrukov, P.S. Bhupal Dev, D. Borah, A. Boyarsky, A. de Gouvea, C.A. de S. Pires, H.J. de Vega, A.G. Dias, P. Di Bari, Z. Djurcic, K. Dolde, H. Dorrer, M. Durero, O. Dragoun, M. Drewes, G. Drexlin, Ch.E. Düllmann, K. Eberhardt, S. Eliseev, C. Enss, N.W. Evans, A. Faessler, P. Filianin, V. Fischer, A. Fleischmann, J.A. Formaggio, J. Franse, F.M. Fraenkle, C.S. Frenk, G. Fuller, L. Gastaldo, A. Garzilli, C. Giunti, F. Glück, M.C. Goodman, M.C. Gonzalez-Garcia, D. Gorbunov, J. Hamann, V. Hannen, S. Hannestad, S.H. Hansen, C. Hassel, J. Heeck, F. Hofmann, T. Houdy, A. Huber, D. Iakubovskyi, A. Ianni, A. Ibarra, R. Jacobsson, T. Jeltema, J. Jochum, S. Kempf, T. Kieck, M. Korzeczek, V. Kornoukhov, T. Lachenmaier, M. Laine, P. Langacker, T. Lasserre, J. Lesgourgues, D. Lhuillier, Y.F. Li, W. Liao, A.W. Long, M. Maltoni, G. Mangano, N.E. Mavromatos, N. Menci, A. Merle, S. Mertens, A. Mirizzi, B. Monreal, A. Nozik, A. Neronov, V. Niro, Y. Novikov, L. Oberauer, E. Otten, N. Palanque-Delabrouille, M. Pallavicini, V.S. Pantuev, E. Papastergis, S. Parke, S. Pascoli, S. Pastor, A. Patwardhan, A. Pilaftsis, D.C. Radford, P.C.-O. Ranitzsch, O. Rest, D.J. Robinson, P.S. Rodrigues da Silva, O. Ruchayskiy, N.G. Sanchez, M. Sasaki, N. Saviano, A. Schneider, F. Schneider, T. Schwetz, S. Schönert, S. Scholl, F. Shankar, R. Shrock, N. Steinbrink, L. Strigari, F. Suekane, B. Suerfu, R. Takahashi, N. Thi Hong Van, I. Tkachev, M. Totzauer, Y. Tsai, C.G. Tully, K. Valerius, J.W.F. Valle, D. Venos, M. Viel, M. Vivier, M.Y. Wang, C. Weinheimer, K. Wendt, L. Winslow, J. Wolf, M. Wurm, Z. Xing, S. Zhou, K. Zuber. J. Cosmology and Astroparticle Phys., 01, (2017). DOI: 10.1088/1475 7516/2017/01/025

[4] I.E. Alekseev, S.V. Bakhlanov, A.V. Derbin, I.S. Drachnev, I.M. Kotina, I.S. Lomskaya, V.N. Muratova, N.V. Niyazova, D.A. Semenov, M.V. Trushin, E.V. Unzhakovet. Phys. Rev. C, **102** (6), (2020). DOI: 10.1103/PhysRevC.102.064329

[5] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A.J. Banday, R.B. Barreiro, N. Bartolo, S. Basak, R. Battye, K. Benabed, J.-P. Bernard, M. Bersanelli, P. Bielewicz, J.J. Bock, J.R. Bond, J. Borrill, F.R. Bouchet, F. Boulanger, M. Bucher, C. Burigana, R.C. Butler, E. Calabrese, J.-F. Cardoso, J. Carron, A. Challinor, H.C. Chiang, J. Chluba, L.P.L. Colombo, C. Combet, D. Contreras, B.P. Crill, F. Cuttaia, P. de Bernardis, G. de Zotti, J. Delabrouille, J.-M. Delouis, E. Di Valentino, J.M. Diego, O. Doré, M. Douspis, A. Ducout, X. Dupac, S. Dusini, G. Efstathiou, F. Elsner, T.A. Enßlin, H.K. Eriksen, Y. Fantaye, M. Farhang, J. Fergusson, R. Fernandez-Cobos, F. Finelli, F. Forastieri, M. Frailis, A.A. Fraisse, E. Franceschi, A. Frolov, S. Galeotta, S. Galli, K. Ganga, R.T. Génova-Santos, M. Gerbino, T. Ghosh, J. González-Nuevo, K.M. Górski, S. Gratton, A. Gruppuso, J.E. Gudmundsson, J. Hamann, W. Handley, F.K. Hansen, D. Herranz, S.R. Hildebrandt, E. Hivon, Z. Huang, A.H. Jaffe, W.C. Jones, A. Karakci, E. Keihänen, R. Keskitalo, K. Kiiveri, J. Kim, T.S. Kisner, L. Knox, N. Krachmalnicoff, M. Kunz, H. Kurki-Suonio, G. Lagache, J.-M. Lamarre, A. Lasenby, M. Lattanzi, C.R. Lawrence, M. Le Jeune, P. Lemos, J. Lesgourgues, F. Levrier, A. Lewis, M. Liguori, P.B. Lilje, M. Lilley, V. Lindholm, M. López-Caniego, P.M. Lubin, Y.-Z. Ma, J.F. Macías-Pérez, G. Maggio, D. Maino, N. Mandolesi, A. Mangilli, A. Marcos-Caballero, M. Maris, P.G. Martin, M. Martinelli, E. Martínez-González, S. Matarrese, N. Mauri, J.D. McEwen, P.R. Meinhold, A. Melchiorri, A. Mennella, M. Migliaccio, M. Millea, S. Mitra, M.-A. Miville-Deschênes, D. Molinari, L. Montier, G. Morgante, A. Moss, P. Natoli, H.U. Nørgaard-Nielsen, L. Pagano, D. Paoletti, B. Partridge, G. Patanchon, H.V. Peiris, F. Perrotta, V. Pettorino, F. Piacentini, L. Polastri, G. Polenta, J.-L. Puget, J.P. Rachen, M. Reinecke, M. Remazeilles, A. Renzi, G. Rocha, C. Rosset, G. Roudier, J.A. Rubiño-Martín, B. Ruiz-Granados, L. Salvati, M. Sandri, M. Savelainen, D. Scott, E.P.S. Shellard, C. Sirignano, G. Sirri, L.D. Spencer, R. Sunyaev, A.-S. Suur-Uski, J.A. Tauber, D. Tavagnacco, M. Tenti, L. Toffolatti, M. Tomasi, T. Trombetti, L. Valenziano, J. Valiviita, B. Van Tent, L. Vibert, P. Vielva, F. Villa, N. Vittorio, B.D. Wandelt, I.K. Wehus, M. White, S.D. M. White, A. Zacchei, A. Zonca. *Planck 2018 results. VI. Cosmological parameters* (2021), arXiv: 1807.06209v4

[6] R.L. Workman, V.D. Burkert, V. Crede, E. Klempt, U. Thoma, L. Tiator, K. Agashe, G. Aielli, B.C. Allanach, C. Amsler, M. Antonelli, E.C. Aschenauer, D.M. Asner, H. Baer, Sw. Banerjee, R.M. Barnett, L. Baudis, C.W. Bauer, J.J. Beatty, V.I. Belousov, J. Beringer, A. Bettini, O. Biebel, K.M. Black, E. Blucher, R. Bonventre, V.V. Bryzgalov, O. Buchmuller, M.A. Bychkov, R.N. Cahn, M. Carena, A. Ceccucci, A. Cerri, R. Sekhar Chivukula, G. Cowan, K. Cranmer, O. Cremonesi, G.D. 'Ambrosio, T. Damour, D. de Florian, A. de Gouvêa, T. DeGrand, P. de Jong, S. Demers, B.A. Dobrescu, M. D'Onofrio, M. Doser, H.K. Dreiner, P. Eerola, U. Egede, S. Eidelman, A.X. El-Khadra, J. Ellis, S.C. Eno, J. Erler, V.V. Ezhela, W. Fetscher, B.D. Fields, A. Freitas, H. Gallagher, Y. Gershtein, T. Gherghetta, M.C. Gonzalez-Garcia, M. Goodman, C. Grab, A.V. Gritsan, C. Grojean, D.E. Groom, M. Grünewald, A. Gurtu, T. Gutsche, H.E. Haber, Matthieu Hamel, C. Hanhart, S. Hashimoto, Y. Hayato, A. Hebecker, S. Heinemeyer, J.J. Hernández-Rey, K. Hikasa, J. Hisano, A. Höcker, J. Holder, L. Hsu, J. Huston, T. Hyodo, Al. Ianni, M. Kado, M. Karliner, U.F. Katz, M. Kenzie, V.A. Khoze, S.R. Klein, F. Krauss, M. Kreps, P. Križan, B. Krusche, Y. Kwon, O. Lahav, J. Laiho, L.P. Lellouch, J. Lesgourgues, A.R. Liddle, Z. Ligeti, C.-J. Lin, C. Lippmann, T.M. Liss, L. Littenberg, C. Lourenço, K.S. Lugovsky, S.B. Lugovsky, A. Lusiani, Y. Makida, F. Maltoni, T. Mannel, A.V. Manohar, W.J. Marciano, A. Masoni, J. Matthews, U.-G. Meißner, I.-A. Melzer-Pellmann, M. Mikhasenko, D.J. Miller, D. Milstead, R.E. Mitchell, K. Mönig, P. Molaro, F. Moortgat, M. Moskovic, K. Nakamura, M. Narain, P. Nason, S. Navas, A. Nelles, M. Neubert, P. Nevski, Y. Nir, K.A. Olive, C. Patrignani, J.A. Peacock, V.A. Petrov, E. Pianori, A. Pich, A. Piepke, F. Pietropaolo, A. Pomarol, S. Pordes, S. Profumo, A. Quadt, K. Rabbertz, J. Rademacker, G. Raffelt, M. Ramsey-Musolf, B.N. Ratcliff, P. Richardson, A. Ringwald, D.J. Robinson, S. Roesler, S. Rolli, A. Romaniouk, L.J. Rosenberg, J.L. Rosner, G. Rybka, M.G. Ryskin, R.A. Ryutin, Y. Sakai, S. Sarkar, F. Sauli, O. Schneider, S. Schönert, K. Scholberg, A.J. Schwartz, J. Schwiening, D. Scott, F. Sefkow, U. Seljak, V. Sharma, S.R. Sharpe, V. Shiltsev, G. Signorelli, M. Silari, F. Simon, T. Sjöstrand, P. Skands, T. Skwarnicki, G.F. Smoot, A. Soffer, M.S. Sozzi, S. Spanier, C. Spiering, A. Stahl, S.L. Stone, Y. Sumino, M.J. Syphers, F. Takahashi, M. Tanabashi, J. Tanaka, M. Taševský, K. Terao, K. Terashi, J. Terning, R.S. Thorne, M. Titov, N.P. Tkachenko, D.R. Tovey,

K. Trabelsi, P. Urquijo, G. Valencia, R. Van de Water, N. Varelas, G. Venanzoni, L. Verde, I. Vivarelli, P. Vogel, W. Vogelsang, V. Vorobyev, S.P. Wakely, W. Walkowiak, C.W. Walter, D. Wands, D.H. Weinberg, E.J. Weinberg, N. Wermes, M. White, L.R. Wiencke, S. Willocq, C.G. Wohl, C.L. Woody, W.-M. Yao, M. Yokoyama, R. Yoshida, G. Zanderighi, G.P. Zeller, O.V. Zenin, R.-Y. Zhu, Shi-Lin Zhu, F. Zimmermann, P.A. Zyla. Progress Theoretical and Experimental Phys., **2022**, 8, (2022). DOI: 10.1093/ptep/ptac097

[7] E.F. Bubnov, A.V. Derbin, I.S. Drachnev, D.V. Ivanov, V.N. Muratova, N.V. Niyazova, M.V. Trushin, E.V. Unzhakov. *Poisk proyavlenia kosmologicheskikh reliktovykh neitrino v β-spektre* ^{210}Bi, preprint — 3074 (NITs „Kurchatovsky Institute“ — PIYAF, Gatchina, 2023)(in Russian), ISBN: 978-5-86763-480-3

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