Testing feasibility of SrI2(Eu) scintillation detector for low-energy neutrino detection

Authors: Strizhak, Dr. Alexander, Ivashkin, Dr. Aleksandr, Baranov, Mr. Alexander, Musin, Mr. Sultan, Tkachev, Dr. Igor, Strizhak, Dr. Alexander

Date: 2026-04-19T17:00:49+00:00

Abstract

The possibility to use the SrI2(Eu) scintillator for detection of tritium neutrino with energy below 20 keV is suggested. SrI2(Eu) scintillator has a record light yield up to 120 photons/keV that in combination with high photon detection efficiency photodetectors would enable the detection threshold below 1 keV. The compact modular setup of SrI2(Eu) scintillation detectors to register sub-keV energy deposition from neutrinos interactions is considered. Each individual detector module comprises four small scintillators with attached SiPM arrays packed together in a light-tight plastic case. The main drawback of SiPM, the high dark current rate (DCR), which is exponentially dependent on temperature, can be suppressed at negative operating temperatures. The experimental tests of SiPMs were performed over a wide temperature range from +20°C to -65°C,that show the DRC reduction for about three orders. To further suppress the effect of DCR, a time coincidences of the signals in each detector module were implemented. The light collection of SrI2(Eu) scintillators with SiPM readout was studied using several γ-ray sources. The optimal operating conditions were examined to provide a minimum energy detection threshold. The normalized light collection achieves 26.3 photoelectron/keV in all range of measured energies. The performed tests with low energy γ-ray sources confirmed that constructed SrI2(Eu) modules are suitable for high-resolution X- and γ-rays spectroscopy.

Full Text

Preamble

Testing feasibility of SrI2 (Eu) scintillation detector for low-energy neutrino detection∗

A. Baranov,1

A. Ivashkin,1

S. Musin,1, 2

A. Strizhak,1, 2, † and

I. Tkachev1

Institute for Nuclear Research RAS, Moscow 117312, Russia Moscow Institute of Physics and Technology, Dolgoprudny 141701, Russia

The possibility to use the SrI2 (Eu) scintillator for detection of tritium neutrino with energy below 20 keV is suggested. SrI2 (Eu) scintillator has a record light yield up to 120 photons/keV that in combination with high photon detection efficiency photodetectors would enable the detection threshold below 1 keV. The compact modular setup of SrI2 (Eu) scintillation detectors to register sub-keV energy deposition from neutrinos interactions is considered. Each individual detector module comprises four small scintillators with attached SiPM arrays packed together in a light-tight plastic case. The main drawback of SiPM, the high dark current rate (DCR), which is exponentially dependent on temperature, can be suppressed at negative operating temperatures. The experimental tests of SiPMs were performed over a wide temperature range from +20 ∘ C to -65 ∘ C,that show the DRC reduction for about three orders. To further suppress the effect of DCR, a time coincidences of the signals in each detector module were implemented. The light collection of SrI2 (Eu) scintillators with SiPM readout was studied using several γ-ray sources. The optimal operating conditions were examined to provide a minimum energy detection threshold. The normalized light collection achieves 26.3 photoelectron/keV in all range of measured energies. The performed tests with low energy γ-ray sources confirmed that constructed SrI2 (Eu) modules are suitable for high-resolution X- and γ-rays spectroscopy.

Keywords

Tritium neutrino, scintillation detector, light yield, energy resolution

INTRODUCTION

with use of the compact photodetectors like silicon photomultiplier (SiPM). The choice of SiPM is driven by several fac32 tors. Thus, PMTs photocathodes are contaminated with the 33 radioactive isotope K, which can potentially lead to false 34 event identification. Silicon photodetectors avoid the prob35 lems with the radioactive contamination. The small size and 36 relatively low cost of SiPMs allow the design photodetector 37 arrays with the required sizes and configurations.

Finally, 38 commercial SiPMs can achieve a Photon Detection Efficiency 39 (PDE) of up to 50%, which is generally higher than quantum 40 efficiency of traditional PMTs. The main drawback of SiPMs 41 is high thermal noise of around 100 kHz/mm at room tem42 perature. However, this issue is less crucial for the CsI(pure) 43 detectors operating at cryogenic temperatures. For example, 44 at liquid nitrogen temperatures, the noise level drops by sev2 45 eral orders of magnitude to 0.2 Hz/mm [8].

Development of experimental setups with extremely low energy detection thresholds is a crucial task of modern neu4 trino physics. For example, in coherent neutrino-nucleus scat5 tering, the energy deposition in detectors is expected to be 6 around or significantly below 1 keV. Similar energies would 7 be detected in experiments with neutrinos from the beta de8 cays of various radioisotopes. Thus in experiment SATURNE 9 [1] with a tritium source to search for the neutrino magnetic 10 moment, the neutrino energy Eν does not exceed 18 keV and 11 the electron recoil energy Te in the detector will be less than 12 1 keV .

To achieve energy thresholds below 1 keV, detectors based 14 on noble gases at temperatures near 0 K are primarily consid15 ered [2, 3]. Another approach involves cryogenic germanium 16 semiconductor detectors [3–5]. Additionally, traditional in17 organic scintillators with high light yield, such as NaI(Tl), 18 NaI(Na), CsI(Tl) are very attractive to construct a large scale 19 detectors due to their availability and relative cheapness. In 20 recent years, many studies focused on pure cesium iodide 21 (CsI(pure)) scintillator to construct the detectors with sub22 keV energy thresholds. CsI(pure) light yield reaches up to 23 120 photons/keV at temperatures below 100 K [6] that re24 quires a liquid nitrogen (LN2) temperature for the operation. 25 In one of recent works [7], a normalized light yield of approx26 imately 33 p.e./keV was obtained for a small CsI(pure) detec27 tor prototype with a cryogenic photomultiplier tube (PMT) 28 readout.

Additional improvement of light collection can be achieved

In the past few years a number of tests were performed with small CsI(pure) scintillators coupled to SiPMs at LN2 48 temperature.

Thus miniature CsI(pure) detector with two 49 SiPMs readout [9] revealed a record light collection of about 50 43 p.e./keV. Larger sizes of scintillators would certainly re51 duce the light collection efficiency due to the light absorption 52 in the crystals. It is especially problematic for CsI(pure) UV 53 emission spectrum with the average wavelength of about 350 54 nm. The problem could be partially solved by coating the 55 SiPM matrices by wavelength shifter [10]. For relatively large 56 5x5x5 cm crystal the light collection achieved 21 p.e./keV 57 at nominal SiPM operation voltage and 30 p.e./keV at ex58 treme overvoltage. In the last case, the signal amplitude is 59 dominated by contribution from parasitic crosstalk of SiPM 60 pixels that provides unrealistic 123 p.e./keV light collection. 61 Note, that crosstalk is a general problem of SiPM operat62 ing at cryogenic temperatures [11]. Also, the performance of ∗ This study was conducted within the framework of the scientific program 63 some SiPM types can be unstable at these temperatures due of the National Center for Physics and Mathematics, section 8 «Physics of 64 to charge carrier freeze-out in semiconductors [8]. hydrogen isotopes». Stage 2026-2027. † Corresponding author,

strizhak@inr.ru

In spite of the excellent light yield of CsI(pure) at LN2 tem-

perature, this scintillator has an inherent disadvantage associ- 121 neutrino detector. At the same time, the choice of the SrI2 (Eu) ated with it' s internal radioactivity, mainly due to the pres- 122 scintillator allows each module to be used as a high-resolution 68 ence of radioisotope Cs [12, 13]. Additionally, CsI(pure) 123 detector for γ—spectroscopy as would be shown below. The 69 emission spectrum lies in UV region, which does not properly 124 use of four SrI2 (Eu) crystals in a single module with a to70 align with SiPM PDE maximum. To overcome the mentioned 125 tal mass of about 100 g and overall dimension of 30x30x25 makes this detector effective for both hard X-rays and 71 drawbacks, other low-background scintillators with compara- 126 mm 72 ble light yields at elevated operating temperatures can be con- 127 γ-radiation. 73 sidered. One of the most attractive scintillators for such mea74 surements is SrI2 (Eu) (Europium-doped Strontium Iodide). It

A. Structure of neutrino detector 75 has superior light yield of up to 120 photons/keV at room 128 76 temperature and nice proportionality of light yield across a 77 wide range of deposited energies [14–16]. This advanced in- 129 The tritium neutrino detector will consist of a few (up to 78 organic scintillator is renowned for its exceptionally high en- 130 seven) vertically placed individual layers, each representing a 79 ergy resolution, significantly surpassing traditional materials 131 separate mini-detector with its own readout system. In a sin80 like NaI(Tl). The best SrI2 (Eu) samples have energy resolu- 132 gle layer the detector modules are arranged along two (outer 81 tion below 3% for the 662 keV Cs gamma line that is a 133 and inner) concentric circles, as shown in figure 1 [Figure 1: see original paper]. 82 factor of 2 better than for NaI(Tl).

The outer and inner circles contain 10 and 6 detector mod83 Comparing to CsI(pure), SrI2 (Eu) demonstrates less in- 135 ules, respectively. The modules of the layer are mounted on 84 ternal radioactivity [17] and appears to be more suitable 136 a copper disk to ensure thermal conductivity. An inner hole 85 for low background measurements. The SrI2 (Eu) emission 137 in the disc is intended for the cooling system and signal ca86 spectrum peaks at 420 nm and nicely aligns with the max- 138 bles. PCB boards with SiPM arrays and individual readout 87 imum spectral sensitivity of SiPMs. These unique proper- 139 are attached to each module.

The weight of the scintilla88 ties make the SrI2 (Eu) scintillator excellent not only for γ- 140 tors in one layer is 1.6 kg providing the total mass of the 89 spectroscopy, but also for detecting ultra-low energies, in 141 SrI2 (Eu) crystals in full detector of 11.2 kg. Parameters of 90 particular, sub-keV energy depositions from neutrino inter- 142 typical SrI2 (Eu) crystal are presented in table 1 . To suppress 91 actions. Of course, the high cost of this scintillator is not suit- 143 the thermal noises of SiPMs full detector will be placed in the 92 able for large-scale detectors. However, SrI2 (Eu) is a promis- 144 refrigerator with the operational temperature between -60°C 93 ing candidate for small-sized neutrino detectors with an ex- 145 and -80°C. 94 tremely low energy threshold, for example, for the scintilla95 tion detector of tritium neutrinos in the SATURNE experiTable

1. Physical and scintillation parameters of SrI2 (Eu). 96 ment [18]. Below, the concept of such detector and the perParameter Value 97 formance of its individual scintillator modules will be considDensity (g/cm3) 98 ered.

CONCEPT OF LOW THRESHOLD SCINTILLATION DETECTOR FOR TRITIUM NEUTRINO

Light Yield (photons/MeV) LY Temp. Coeff. (%/◦

C) Energy Resolution (FWHM) @ 662 keV Primary Decay Time (µs) Emission Peak (nm) Refractive Index Effective Atomic Number (Z) Hygroscopicity

80,000–120,000 −0.12 2.6–4.0%

The SATURNE experiment [1, 18] is being developed at the National Center for Physics and Mathematics (NCPM) 103 in Sarov, Russia, and will search for neutrino electromag104 netic interactions, including the neutrino magnetic moment. 146 Since each detector layer consists of 16 modules with 64 105 The experiment will employ a high-intensity tritium neutrino 147 detector elements (SrI2 (Eu) crystals), it requires 64 readout 106 source with a total tritium mass of at least 1 kg and initial ac- 148 channels. Each channel includes a current amplifier of SiPM 107 tivity of 10 MCi. The tritium neutrino source [19] is a set of 149 signal and an analog-to-digital converter (ADC). A commer108 tubular elements, in which tritium is in a chemically bound 150 cial 64-channel ADC will allow each layer to function as an 109 state on titanium. At the initial stage of experiment, these 151 independent mini-neutrino detector with its own data acquisi110 tubular elements will form the cylinder with the inner diam- 152 tion system (DAQ). DAQ is based on the ADC64s2 board, de111 eter and height of about 300 mm both. The scintillation de- 153 signed by AFI Electronics. This board integrates 64 channels 112 tector will be situated in the inner part of this cylinder. The 154 of 12-bit analog-to-digital converters with the sampling rate 113 limited active volume necessitates the maximal packing den- 155 of 62.5 MS/s and additionally includes noise filters and dif114 sity of detector elements. At the same time, these elements 156 ferential amplifiers on a custom-designed mezzanine printed 115 must be read out by photodetector arrays of SiPMs with a 157 circuit board. The recorded by the ADC waveforms are ana116 reasonable density of readout channels. These factors moti- 158 lyzed to extract both amplitude and timing information. 117 vated the development of a modular structure of the detec- 159 Note that operation of the SrI2 (Eu) detector at a relatively 118 tor, where each module represents a small individual detector 160 high temperature above -100°C allows the use of commercial 119 with its own independent readout. Combination of these de- 161 cooling systems such as medical refrigerators and avoids nu120 tector modules would allow to construct different geometry of 162 merous problems associated with cryogenic systems. At the

SiPM arrays and individual readout is attached to each module. The modules of the layer are mounted on a copper disk to ensure acceptable thermal conductivity. An inner hole is intended for the cooling system and signal cables. Right - a scheme of the neutrino detector that includes seven adjacent layers. Each layer is readout its own analog-to-digital converter and can be considered as independent part of full detector.

same time, the thermal noise of SiPM will be several orders of 192 the impermeability of the construction. For this purpose the magnitude higher compared to the LN2 temperature. It would 193 plastic container is covered by waterproofing varnish. The 165 require and additional approaches in SiPM noise suppression 194 most problematic issue is humidity insulation of the optical 166 as time coincidence of signals in SrI2 (Eu) crystals. The noise 195 contact between the scintillator and SiPM array. Ordinary op167 suppression methods developed are described in detail below. 196 tical grease can not guarantee the water-tightness, while the The proposed structure of the neutrino detector ensures its 197 optical glue causes damage to the SiPM arrays if module re169 modularity and scalability, which allows further improving 198 pair is needed. Therefore, the optical contact is provided by 170 the sensitivity of the detector by increasing the number of lay- 199 a transparent double-sided acrylic tape. A dedicated study 200 showed that in this case, light collection is deteriorated by 171 ers of detector modules. 201 approximately 10–15% compared to optical grease. This is 202 a reasonable price for the ability to reassemble the detector 203 modules.

B. Design of detector modules Note, that the polishing of the SrI2 (Eu) crystals and assem205 bly of detector modules is performed in a dry atmosphere in The structure of individual detector module is shown in 174 figure 2 [Figure 2: see original paper].

It comprises four SrI2 (Eu) crystals, read out by 206 a plexiglass glove box. 175 four photodetector arrays.

Each crystal has dimensions of 176 15$×15×$25 mm and mass of 25 g, with a total active mass

III. READOUT OF DETECTOR MODULES 177 of one module 100

g. Each crystal is wrapped in polytetraflu178 oroethylene (PTFE) reflector tape from all sides except the

A. Performance of photodetectors 179 side used for light readout. The SrI2 (Eu) crystal length of 25 180 mm was chosen to be transparent to its own emission light 181 [20]. The 15\$$\times 15 mmscintillatorcross - sectionfitstosizes209Toensurethehighestcollectionefficiencyofthelightfrom182ofusedSiPMarrays.Every$ mm . Geometri- 211 quested.

Currently, one of the best commercial SiPM op184 cal factor (ratio of SiPM active area to the transverse crystal 212 tions with high PDE is Hamamatsu MPPC S14161-3050HS2 185 size) leads to 25 percent light loss. 213 04 13 × 13 mm . Maximum PDE of the Hamamatsu MPPC The mechanical design of the detector modules is based on 214 exceeds 50% at a light wavelength of 420 nm. Main parame187 a four-cells plastic honeycomb structure manufactured using 215 ters of the selected SiPM matrices are shown in table 2 The second important parameter that limits the energy de188 a 3D printer. The wrapped in Teflon SrI2 (Eu) crystals are in- 216 189 serted in these cells. In figure 2 (right) the assembled module 217 tection threshold is the Dark Current Rate (DCR), which is 190 with board of SiPM arrays is shown. Since the SrI2 (Eu) scin- 218 mainly caused by SiPM thermal noises. Together with PDE, 191 tillator is strongly hygroscopic, the special attention is paid to 219 DCR is the principal limiting factor, especially in the detec163

one of the ends. Crystals are placed in a plastic honeycomb structure. Right – assembled module with board of SiPM arrays.

First, number of events in spectrum reflects the DCR, i.

e. the

3050HS-04 SiPM array for T = 25 ◦

C. 240 individual peaks equals to the amplitude (or charge) of singleParameter Value 241 photoelectron signals. This allows for immediate calibration Number of channels 16 (4 ×

4) 242 of the amplitude scale in absolute units and the derivation of Effective area per ch (mm2) 243 signal amplitudes as the number of photoelectrons (see secPixel pitch (µm) 244 tion IV for details). Third, the ratio of the number of events Spectral response (nm) 245 with an amplitude greater than the amplitude of a single phoPeak sensitivity λp (nm) 246 toelectron to the number of a single-photoelectron events is PDE @ λp (%) 247 an estimate of X-talk probability.

Gain (typ.) 2.5 × 106 The thermal noise spectra were collected for SiPMs in a Breakdown voltage VBR (V) VBR Temp. Coeff. (mV/◦

C) 249 wide temperature range. The experimental setup incorporated Dark count per ch (kcps) 250 two cooling systems: a standard commercial freezer with a

minimum temperature of -35◦ C and a medical-grade freezer 252 capable of cooling down to -65

C. All DCR measurements 220 tion of rare events. As mentioned above, DCR drops sharply 253 were obtained using a detection threshold close to 0.5 photo5 221 with decreasing operating temperature from 10 Hz/mm2 at 254 electron amplitude. 222 room temperature to below 1 Hz/mm at LN2 temperature. 255 The dependence of DCR on the operating temperature for 223 Since the SrI2

(Eu) neutrino detector is planned to operate at 256 the Hamamatsu MPPC array is presented in figure 4 [Figure 4: see original paper] in a 224 a relatively high temperature above -100°C, the DCR is ex- 257 logarithmic scale. Several measurements at various operat2 225 pected to be several tens of Hz/mm . Such relatively high 258 ing voltages are presented. The MPPC manufacturer recom226 DCR value would require the development of additional ap- 259 mends an overvoltage of 2.7 V above the breakdown voltage. 227 proaches to suppress the contribution of thermal noises in the 260 To test the effect of overvoltage on the DCR, data were also 228 false event rate, such as the time coincidence of the SiPM 261 collected at overvoltages of 2.2 V and 3.2 V, i.

e. 0.5 V be229 signals discussed below. 262 low and above the recommended value. As can be seen, the To characterize the SiPMs, the dark current rate and cross- 263 dark current rate varies from 29 kHz/mm2 at room temper2 at -65 ∘

C. Different overvoltage values 231 talk (X-talk) values were studied using the SiPM thermal 264 ature to 41 Hz/mm 232 noise spectra collected at different temperatures. 234 trum for SiPM thermal noise signals. Individual peaks cor- 267 in good agreement with the expected exponential behavior.

Note that increasing the overvoltage will improve the PDE 235 respond to different number of thermally activated pixels of 268 236 SiPM array or, equivalently, to different number of photo- 269 value, but at the cost of a significant increase in X-talk, see, This results in a significant fraction of 237 electrons. This spectrum allows us to find three parameters. 270 for example, [10].

ADC channels

DCR (Hz/mm)

pixels of SiPM (to different number of photoelectrons). A four-Gaussian fit was applied to precisely identify the average positions of these peaks. Each group of three parameters represent the amplitude, mean position, and standard deviation of the corresponding Gaussian component.

Counts

Temperature (°C) dependencies for Hamamatsu arrays correspond to different over-voltages of 2.2, 2,7 and 3.2

V. DCR values for room and -65° C temperatures are shown numerically.

events with multiple photoelectron signals generated by ther- 278 noise level of silicon photomultipliers is reduced to below mal noise, and should be avoided in detectors with ultra-low 279 one Hz/mm2 [8]. As shown above, the DCR at -65 ∘ C is two 273 threshold. Measured at -65 C and nominal voltages, X-talk 280 orders of magnitude higher. Therefore, additional noise sup274 value is about 7% for all tested MPPC arrays. 281 pression techniques are required. One of the most effective 282 methods is the use of time coincidences of the signals in each 283 event.

It can potentially suppress the detection of random 284 thermal noises by several orders of magnitude.

B. Time coincidence trigger scheme

This approach is implemented in the readout of each detecThe operating temperature of -65 ∘ C is significantly higher 286 tor module. The use of four SrI2 (Eu) crystals and the same 277 than the liquid nitrogen temperature, at which the thermal 287 number of SiPM arrays in a single detector module allows

The presented readout encoding scheme preserves the number of readout channels equal to the number of SrI2 (Eu) 307 crystals in the detector module, but requires a specific event 308 selection to trigger ADC recording in case of double coinci309 dence of appropriate signal combination. For this purpose, a 310 dedicated trigger scheme with four coincidence circuits was 311 implemented, as shown in 5 (bottom). An event firing one 312 of the crystals triggers two adjacent SiPM groups and coin313 cidence of these two signals generates the ADC trigger for 314 the event recording. Since one detector module uses four co315 incidence circuits, the trigger signals are fed to the common 316 OR-circuit. Taking into account the measured DCR and a 317 coincidence time of the order of one microsecond, the trig318 ger frequency from random thermal noise is estimated to be 319 several tens of hertz for one detector module if the detection 320 threshold is set to about 0.5 photoelectrons. This trigger rate 321 is rather comfortable for the data acquisition by ADC.

PERFORMANCE OF SRI2 (EU) DETECTOR

Discriminator

The characteristics of the detector module were studied using SrI2 (Eu) crystals manufactured by the A.

N. Nikolaev InOR 325 stitute of Inorganic Chemistry (NIIC SB RAS, Novosibirsk, 326 Russia).

Since the crystal growth technology is currently 327 under development, crystals may exhibit variations in impu6 328 rity levels and activator distribution. Therefore, the follow7 329 ing results are presented for a high-quality specimen. HamaAND 330 matsu MPPC S14161-3050HS-04 photodetectors were used 331 for light readout, and signal waveforms were recorded by a 332 12-bit ADC with a 16 ns sampling rate.

The examples of such waveforms are presented in figure tor module. The colors represent four SiPM groups with individual 334 6 for the low (left panel) and high (right panel) energy designal readout. Half of SiPM array of one crystal is combined with 335 positions in scintillator. Small peaks at left picture correthe other half of the SiPM array of the adjacent crystal. Bottom - 336 spond to the detection of single photoelectrons. The widths of scheme of event trigger with four coincidence circuits to suppress 337 these single electron signals of about 0.5 µs is determined by the thermal noises. An event firing one of the crystals triggers two 338 the terminal capacitance of MPPC array. It can be seen that adjacent SiPM groups of different colors (see left picture) and gen- 339 the full pulse width from the SrI (Eu) scintillator is approxi2 erates the ADC trigger signal for event recording. 340 mately 10 µs. Therefore, the signal charge was also integrated 341 over 10 µs.

Light collection tests of SrI2 (Eu)-SiPM detectors were per288 the appropriate configuration of photodetectors to arrange the 343 formed with 241 Am, 55 Fe and 57 Co sources of gamma-rays, 289 time signal coincidence in each scintillator without increas- 344 which cover the energy range from a few keV to about 120 290 ing the number of readout channels. The simplest solution 345 keV. All used sources were below exemption activity thresh291 to implement the time coincidence of signals is to divide the 346 old.

The light yield estimation was done in several steps. 292 SiPM array in each crystal into two equivalent parts with in- 347 The initial step involved calibration of the ADC scale in 293 dependent signal readout. However, such basic configuration 348 photoelectrons (p.e.) using a few photoelectron peaks from 294 results in doubling of the number of electronic readout chan- 349 the SiPM noise spectrum (see figure 3 [Figure 3: see original paper]). The four observed 295 nels. To avoid this drawback, a method for encoding the read- 350 peaks were fitted by the superposition of four Gaussian func296 out channel was developed using the structure of a detector 351 tions, with the i-th peak characterized by p 3i−3 (number of 297 module consisting of four SrI2 (Eu) crystals. Namely, half of 352 events), p (mean), (standard deviation, σ) pa3i−2 298 SiPM array of one crystal was connected in parallel with the 353 rameters. Based on this fit, the photoelectron conversion fac299 other half of the SiPM array of the adjacent crystal. 354 tor was determined to be 1 p.

e. = 30100 ± 300 ADC chan300 The SiPMs are organized into four distinct groups, as indi- 355 nels as the average distance between fitted peaks. Note that 301 cated by different colors in figure 5 [Figure 5: see original paper] (top). Each SiPM group is 356 during acquisition of the noise spectrum an additional 10× 302 readout by a single electronic channel. And the fired SrI2 (Eu) 357 gain was implemented to improve the sensitivity of ADC. 303 crystal is uniquely identified by the combination of two sig- 358 As a result, the correct photoelectron conversion factor is 359 1 p.

f. = 3010 ± 30 ADC channels. 304 nals in different readout channels.

Discriminator

Trigger

Discriminator

Discriminator

single p.

e. peaks

Counts

corresponding to the 122 keV gamma line from 57 Co decay. Full signal width is about 10 µs.

ADC channels 241 Am amplitude spectrum. The left cluster of peaks corresponds to gamma energies of 13.9 keV, 17.8 keV, and 20.7 keV, while the right peak indicates the dominant 59.5 keV gamma line from alpha decay. Each group of three parameters in p0 − p8 range represents the amplitude, mean, and standard deviation of a Gaussian component.

362 emission lines at 13.9 keV, 17.8 keV, 20.8 keV, and 59.5 keV. 380 background exhibits a flat behavior in the region of interest, 363 Due to the limited energy resolution the lower-energy peaks 381 enabling reliable Gaussian peak fitting as demonstrated from 364 (13.9-20.8 keV) are partially resolved. Therefore, a triple-382 the fit parameters. The figure 8 [Figure 8: see original paper] (right) presents the energy Co, showing the dominant 122.1 keV gamma 365 Gaussian function to resolve the overlapping peaks was used, 383 spectrum of 366 as shown in the left panel of the histogram. The fitting pa- 384 line and the 14.4 keV nuclear transition line, with correspond367 rameters follow the same convention as for the noise spec- 385 ing Gaussian fit parameters presented near each photopeak. 368 trum analysis (see figure 3), with coefficients corresponding 386 In table 3 LY and energy resolution results for tested samples 369 to the amplitude, mean position, and standard deviation of 387 are demonstrated. 370 each Gaussian component. The right panel in figure 7 [Figure 7: see original paper] dis388 The energy dependence of the light yield for all used 371 plays the Gaussian fit results for the well-resolved 59.5 keV 389 gamma-ray peaks is presented in figure 9 [Figure 9: see original paper] (top). The SrI2 (Eu) 372 photopeak. The light yield was determined to be 26.0 by an390 detector exhibits excellent linearity in light output across the 373 alyzing the 59.5 keV photopeak. Similar procedure was ap391 measured energy range (5.9–122.1 keV). The systematic un241 374 plied for other low-energy gamma lines of 392 certainty in the peak positions was estimated from the stan360

source (blue histogram), featuring the characteristic 5.9 keV 394 the light yield data provides an average value of 26.3 ± 0.5 377 Mn Kα X-ray emission line. Due to the low source activity, 395 p.e./keV. The bottom panel of figure 9 shows the energy reso375

Counts

Counts

ADC channels

ADC channels

Energy (Isotope) LY (p.e./keV) Resolution σE /E (%) 5.9 keV (55 Fe) 23.3 ± 4.5 19.47 ± 0.54 13.9 keV (241 Am) 26.3 ± 2.2 8.51 ± 0.16 14.4 keV (57 Co) 28.5 ± 2.3 8.13 ± 0.20 17.8 keV (241 Am) 25.9 ± 1.9 7.48 ± 0.13 20.8 keV (241

Am) 26.8 ± 2.0 7.32 ± 0.21 59.5 keV (241 Am) 26.0 ± 1.0 3.75 ± 0.01 122.1 keV (57 Co) 26.2 ± 0.7 2.61 ± 0.01

lution (σE /E) as a function of gamma-ray energy. The results 397 follow the expected dependence, consistent with the theoretσE 398 ical resolution function , where experimenE =

$ $2 / ndf

1.607 / 6 26.29 ± 0.4921

$ $2 / ndf

Energy (keV) 8.668 / 6 0.2955 ± 0.005535

E(keV)

tally acquired p0 equals 29.5%. Notably, the achieved resolu241 400 tion made it possible to separate closely spaced Am lines 401 at 13.9 keV, 17.8 keV and 20.8 keV (see Fig. 7), which is a 402 challenging task for scintillation detectors due to their typi404 cally limited energy resolution at low energies.

Light Yield (p.e./keV)

significantly deviates from the background profile. Right - 57 Co spectrum. The left peak indicates a gamma energy of 14 keV, and the right peak corresponds to the 122 keV gamma line.

Energy (keV)

CONCLUSION

A novel concept for a low temperature scintillation detecSrI2 (Eu) detector for all used gamma lines. 407 tor utilizing SrI2 (Eu) crystals is proposed for tritium neutrino 408 detection. The SrI2 (Eu) scintillator demonstrates extremely 409 high light yield of up to 120 photons/keV, which potentially 422 ergy range below 20 keV. The use of four SrI2 (Eu) crystals 410 enables to lower the energy detection threshold to hundreds 423 in a single module with an overall dimension of 30x30x25 411 eV. Additionally, SrI2 (Eu) offers other crucial advantages: 424 mm also might allow this detector to be effective for high412 low intrinsic radioactivity and optimal matching of its spectral 425 resolution X- and γ-rays spectroscopy. 413 emission peak with photon detection efficiency of commer414 cially available silicon photomultipliers. SrI2 (Eu) can operate 415 at a convenient temperature of about -65 C, where the DCR 416 of SiPMs is low enough to suppress thermal noises by appli417 cation of time coincidence technique. Systematic measure418 ments of the prototype detector module' s performance using 419 different gamma sources demonstrate consistent light yield 420 of about 26.3 p.e./keV. The obtained energy resolution allows 421 separation of closely spaced Am gamma lines in the en406

[1]

O. Moskalev,

A. Yukhimchuk,

I. Maksimkin,

M. Loginov, 487

2024. doi: 10.1140/epjc/s10052-024-12800-y .

V. Baluev,

R. Musyaev,

M. Vyalkov,

M. Verkhovtsev,

A. Stu- 488 [11]

M.

G. Boulay et al., "SiPM cross-talk in liquid argon de428 denikin,

K. Kouzakov,

V. Trofimov, 489 tectors," Front. in Phys., vol. 11,

p. 1181400,

2023. doi: and

V. Eremin, "On Implementation of the SATURNE Project,"490 10.3389/fphy.2023.1181400 .

Moscow University Physics Bulletin, vol. 79, pp. 252–255, 491 [12]

H. Lee,

H. Bhang,

I. Hahn,

M. Hwang,

H. Kim,

S. Kim, Dec.

2024. doi: 10.3103/S002713492470173X .

S. Kim,

S. Kim,

T. Kim,

Y. Kim,

J. Kwak,

Y. Kwon, [2]

D. Akimov,

A. Berdnikova,

V. Belov,

A. Bolozdynya,

A. Bu- 493

J. Lee,

J. Lee,

M. Lee,

J. Li,

S. Myung,

H. Park, and renkov,

Y. Efremenko,

Y. Gusakov,

A. Etenko,

V. Kaplin, 494

J. Zhu, “Development of low-background CsI(Tl) crystals for

A. Khromov,

A. Konovalov,

A. Kovalenko,

E. Kozlova, 495 WIMP search,” Nuclear Instruments and Methods in Physics

A. Kumpan,

T. Krakhmalova,

Y. Melikyan,

P. Naumov, 496 Research Section A: Accelerators, Spectrometers, Detectors

D. Rudik,

R. Shafigullin, and

I. Tolstukhin, “RED-100 de- 497 and Associated Equipment, vol. 571, no. 3, pp. 644–650,

2007. tector for the first observation of the elastic coherent neu- 498 doi: 10.1016/j.nima.2006.10.325 . trino scattering off xenon nuclei,” Journal of Physics: Confer- 499 [13]

Y. Kim,

I. Hahn,

M. Hwang,

L. Jin,

W. Kang,

H. Kim, ence Series, vol. 675,

p. 012016, 02

2016. doi: 10.1088/1742- 500

S. Kim,

S. Kim,

S. Kim,

T. Kim,

J. Kwak,

Y. Kwon,

E. Lee, 6596/675/1/012016 .

H. Lee,

J. Lee,

J. Lee,

M. Lee,

S. Myung,

H. Park,

A. Schiedt, [3]

J.

I. Collar,

N.

E. Fields,

M. Hai,

T.

W. Hossbach,

J.

L. 502

H. Yang, and

J. Zhu, "Inhibition of Cs137 contamination in Orrell,

C.

T. Overman,

G. Perumpilly, and

B.

J. Scholz, 503 cesium iodide," Nuclear Instruments and Methods in Physics "Coherent neutrino-nucleus scattering detection with a CsI[Na] 504 Research Section A: Accelerators, Spectrometers, Detectors scintillator at the SNS spallation source," Nuclear Instruments 505 and Associated Equipment, vol. 552, no. 3, pp. 456–462,

2005. & Methods in Physics Research Section A-accelerators 506 doi: 10.1016/j.nima.2005.06.080 .

Spectrometers Detectors and Associated Equipment, vol. 507 [14]

M. Takabe,

A. Kishimoto,

J. Kataoka,

S. Sakuragi, and 773, pp. 56–65,

2014. [Online]. Available: https://api. 508

Y. Yamasaki, "Performance evaluation of newly developed semanticscholar.org/CorpusID:119111977 SrI2(Eu) scintillator," Nuclear Instruments and Methods in [4]

A.

G. Beda,

E.

V. Demidova,

A.

S. Starostin,

V.

B. Brudanin, 510 Physics Research Section A: Accelerators, Spectrometers,

V.

G. Egorov,

D.

V. Medvedev,

M.

V. Shirchenko, and

T. Vylov, 511 Detectors and Associated Equipment, vol. 831, pp. 260–"GEMMA experiment: Three years of the search for the neu- 512 264,

2016. doi: 10.1016/j.nima.2016.04.043 ., proceedings trino magnetic moment," Phys. Part. Nucl. Lett., vol. 7, pp. 513 of the 10th International "Hiroshima" Symposium on the 406–409,

2017. doi: 10.1134/S1547477110060063 .

Development and Application of Semiconductor Tracking [5]

C.

E. Aalseth,

P.

S. Barbeau,

J. Colaresi,

J.

I. Collar, 515 Detectors.

J. Diaz Leon,

J.

E. Fast,

N.

E. Fields,

T.

W. Hossbach, 516 [15]

N.

J. Cherepy,

P.

R. Beck,

S.

A. Payne,

E.

L. Swanberg,
A. Knecht,
M.
S. Kos,
M.
G. Marino,
H.
S. Miley,
M.
L. 517
B.
M. Wihl,
S.
E. Fisher,
S. Hunter,
P.
A. Thelin,
C. J.
Miller,
J.
L. Orrell, and
K.
M. Yocum, “CoGeNT: A search for 518 Delzer,
S. Shahbazi,
A. Burger,
K.
S. Shah,
R. Hawrami, low-mass dark matter using p-type point contact germanium 519
L.

A. Boatner,

M. Momayezi,

K. Stevens,

M.

H. Randles, detectors," Phys. Rev. D, vol. 88,

p. 012002, Jul

2013. doi: 520 and

D. Solodovnikov, "History and current status of strontium 10.1103/PhysRevD.88.012002 . iodide scintillators," Hard X-Ray, Gamma-Ray, and Neutron [6]

M. Moszyński,

M. Balcerzyk,

W. Czarnacki,

M. Kapusta, 522 Detector Physics XIX, vol. 10392,

p. 1039202,

2017. doi:

W. Klamra,

P. Schotanus,

A. Syntfeld,

M. Szawlowski, and 523 10.1117/12.2276302 .

V. Kozlov, "Energy resolution and non-proportionality of 524 [16]

E.

V. van Loef,

C.

M. Wilson,

N.

J. Cherepy,

G. Hull,

S.

A. the light yield of pure CsI at liquid nitrogen temperatures," 525 Payne, W.-S. Choong,

W.

W. Moses, and

K.

S. Shah, "Crystal Nuclear Instruments and Methods in Physics Research 526 growth and scintillation properties of strontium iodide scintil466 Section A: Accelerators, Spectrometers, Detectors and 527 lators," IEEE Transactions on Nuclear Science, vol. 56, no. 3, Associated Equipment, vol. 537, no. 1, pp. 357-362,

2005. 528 pp. 869-872,

2006. doi: 10.1109/TNS.2009.2013947 . doi: 10.1016/j.nima.2004.08.043 ., proceedings of the 7th 529 [17]

P. Belli,

R. Bernabei,

F. Cappella,

V. Caracciolo,

R. Cerulli, International Conference on Inorganic Scintillators and their 530

F. Danevich,

A. Incicchitti,

D. Kasperovych,

V. Merlo, Use in Scientific adn Industrial Applications.

O. Polischuk, and

V. Tretyak, "The Future Role of Inorganic [7]

K. Ding,

D. Chernyak, and

J. Liu, "Light yield of cold 532 Crystal Scintillators in Dark Matter Investigations," Instru472 undoped CsI crystal down to 13 keV and the application of 533 ments, vol. 5, no. 2,

2021. doi: 10.3390/instruments5020016 . such crystals in neutrino detection," The European Physical 534 [18]

M. Cadeddu,

F. Dordei,

C. Giunti,

K. Kouza474 Journal C, vol. 80, no. 12,

p. 1146, Dec

2020. doi: 535 kov,

F. Lazarev,

O. Moskalev,

I. Stepantsov,

A. Studenikin, 10.1140/epjc/s10052-020-08712-2 .

V. Trofimov,

M. Verkhovtsev,

M. Vyalkov, [8]

F. Liu,

X. Fan,

X. Sun,

B. Liu,

J. Li,

Y. Deng,

H. Jiang, 537

A. Yukhimchuk, and

E. Zagirdinova, “SATURNE: Current sta477

T. Jiang, and

Y. P, “Characterization of a Mass-Produced 538 tus and physics potential,” Int.

J. Mod. Phys. E, vol. 33, no. 11, SiPM at Liquid Nitrogen Temperature for CsI Neutrino 539

p. 2441011,

2024. doi: 10.1142/S0218301324410118 .

Coherent Detectors,” Sensors, vol. 22, no. 3,

2022. doi: 540 [19]

A.

A. Yukhimchuk,

Y. Vinogradov,

A.

N. Golubkov,

S.

K. 10.3390/s22031099 .

Grishechkin,

R.

I. Il’ kaev,

A.

V. Kuryakin,

B.

L. Lebedev, [9]

K. Ding,

J. Liu,

Y. Yang, and

D. Chernyak, “First operation 542

V.

N. Lobanov,

V.

N. Mikhailov,

D.

P. Tumkin, and

L.

N. of undoped csi directly coupled with sipms at 77 k,” The 543 Bogdanova, “Status of works on a-40-mci-activity tritium European Physical Journal C, vol. 82, no. 4,

p. 344, Apr

2022. 544 source for the measurement of the antineutrino magnetic doi: 10.1140/epjc/s10052-022-10289-x . moment,” Fusion Science and Technology, vol. 48, no. 1, pp. 485 [10]

L. Wang et al., “Reactor neutrino physics potentials of cryo- 546 731–736,

2005. doi: 10.13182/FST05-A1026 . genic pure-CsI crystal,” Eur. Phys.

J. C, vol. 84, no. 4,

p. 440,

[20]

M.

S. Alekhin,

K.

W. Krämer, and

P. Dorenbos, “Self-absorption in SrI2:2Eu2+ between 78K and 600K,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 714, pp. 13-16,

2013. doi: 10.1016/j.nima.2013.02.025 .