Перспективные эксперименты по поиску безнейтринного двойного бета-распада в БНО ИЯИ РАН

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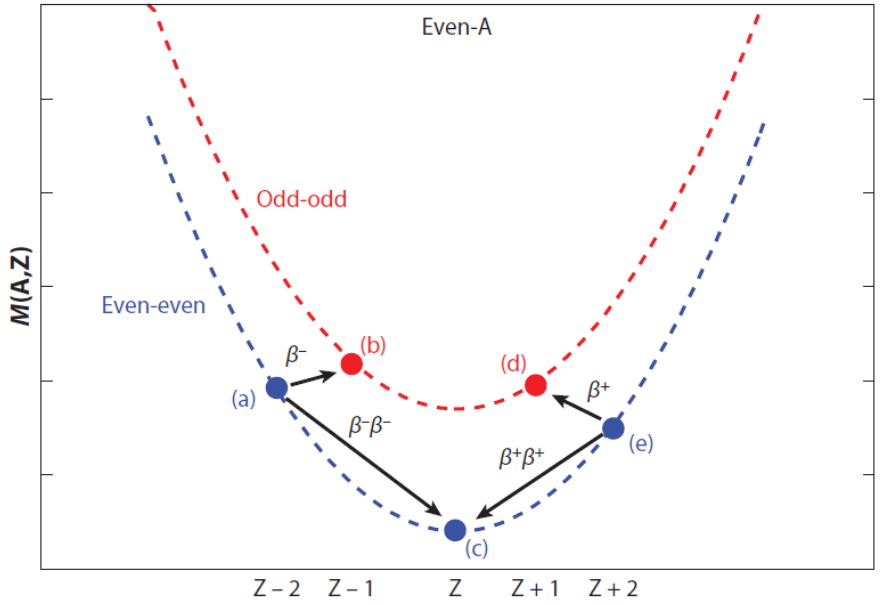
посвященная 70-летию со дня рождения академика РАН
Валерия Анатольевича Рубакова
Москва, 2025

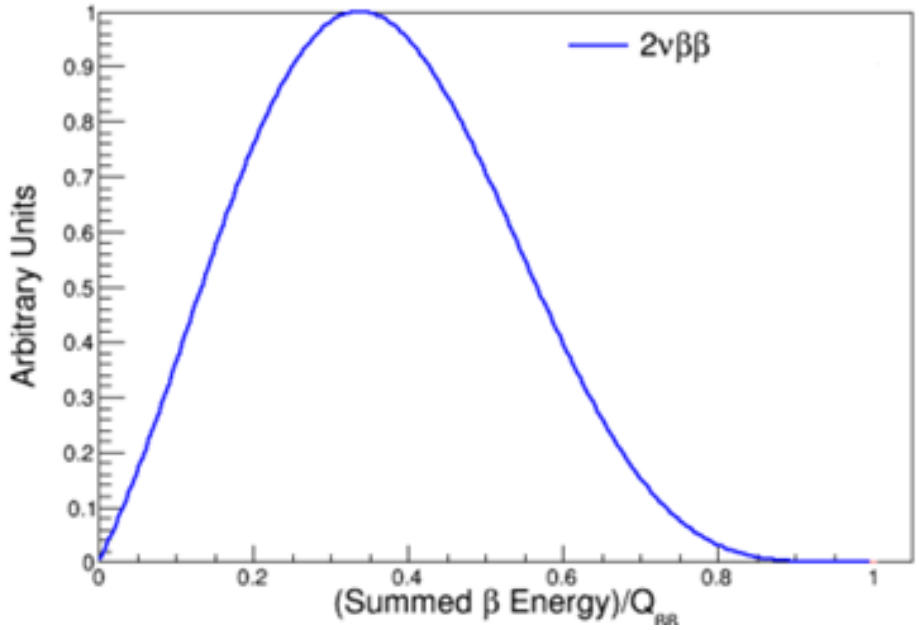
Двойной двухнейтринный бета-распад ($2\nu\beta\beta$)

Двойной двухнейтринный бета-распад – редчайший наблюдаемый слабый ядерный процесс.

$$\beta^-\beta^- : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e,$$
$$\beta^+\beta^+ : (A, Z) \rightarrow (A, Z-2) + 2e^+ + 2\nu_e,$$
$$\mathrm{ECEC} : 2e^- + (A, Z) \rightarrow (A, Z-2) + 2\nu_e,$$
$$\mathrm{EC}\beta^+ : e^- + (A, Z) \rightarrow (A, Z-2) + e^+ + 2\nu_e$$

$$Q_{\beta\beta} = M(A, Z) - M(A, Z+2)$$

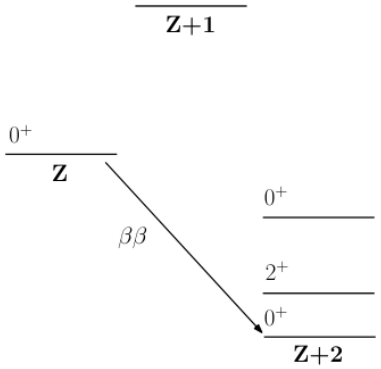




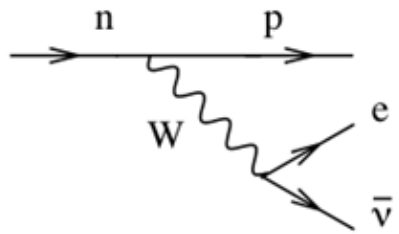
In nature
we only observe
ν_L and $\bar{\nu}_R$

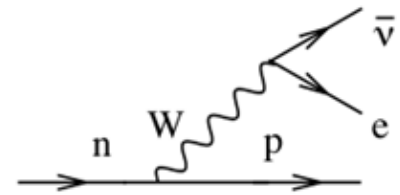
Dirac neutrino

$\nu \neq \bar{\nu}$

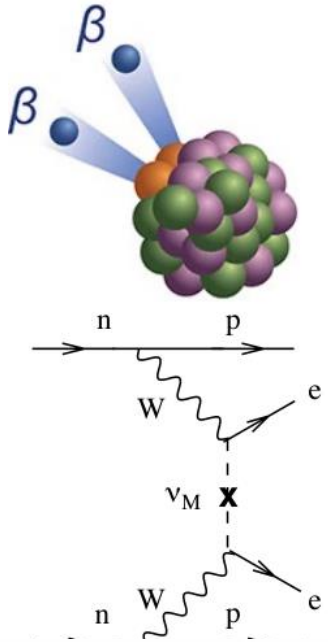


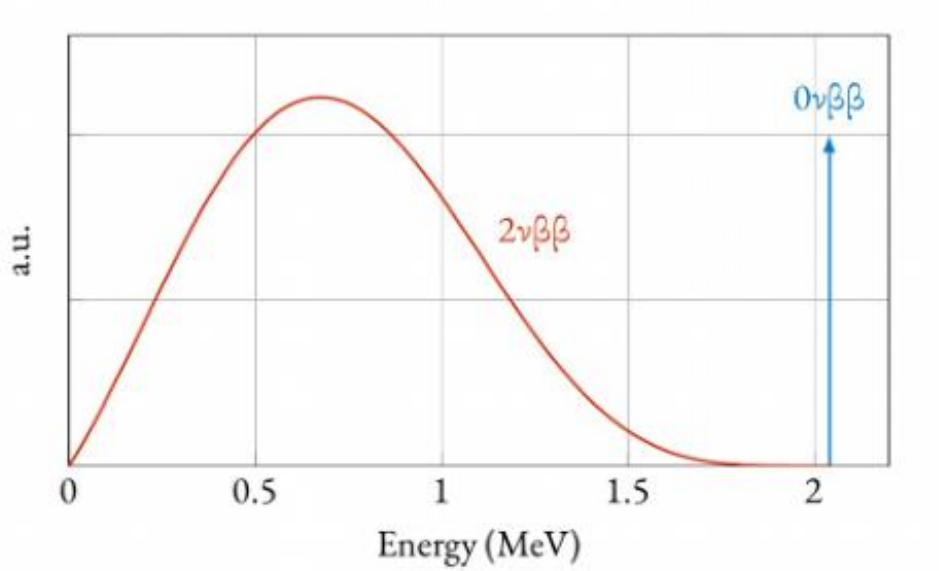
F. Avignone *et al.* Rev. Mod. Phys. 2008





Безнейтринный двойной бета-распад ($0\nu\beta\beta$)





В поисках теоретического процесса:

$(A,Z) \rightarrow (A, Z+2) + 2e^-$

В отличие от: $(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

Чем интересны эксперименты по 2β-распаду?

- Несохранение лептонного числа (**ΔL=2**)
- Природа массы нейтрино (**Dirac or Majorana?**).
- Абсолютная шкала масс (величина или предел на $\mathbf{m_1}$).
- Тип иерархии (нормальная, обратная, квази-вырожденная).
- **CP** нарушение в лептонном секторе.

Majorana neutrino

$\nu = \bar{\nu}$

1937 год

That's because they are simply just ν_L and ν_R

Наиболее интересные с экспериментальной точки зрения изотопы и их ключевые особенности

В природе существует 35 изотопов, способных к двойному бета-распаду.

^{48}**Ca**, ^{70}Zn, ^{76}Ge, ^{82}**Se**, ^{86}Kr, ^{94}Zr, ^{96}**Zr**, ^{98}Mo, ^{100}**Mo**, ^{104}Ru, ^{110}Pd, ^{114}Cd, ^{116}Cd, ^{122}Sn, ^{124}Sn, ^{128}Te, ^{130}Te, ^{134}Xe, ^{136}Xe, ^{142}Ce, ^{146}Nd, ^{148}Nd, ^{150}**Nd**, ^{154}Sm, ^{160}Gd, ^{170}Er, ^{176}Yb ^{186}W, ^{192}Os, ^{198}Pt, ^{204}Hg

Table 1 The most experimentally feasible isotopes and their key features

Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G^{2\nu}$ (10^{-18} year^{-1})
^{48}Ca	0.187	4.263	15.6
^{76}Ge	7.8	2.039	0.0482
^{82}Se	9.2	2.998	1.60
^{96}Zr	2.8	3.348	7.83
^{100}Mo	9.6	3.035	4.13
^{116}Cd	7.6	2.813	3.18
^{130}Te	34.08	2.527	1.53
^{136}Xe	8.9	2.459	1.43
^{150}Nd	5.6	3.371	36.4

The phase-space factors $G^{2\nu}$ are from Reference 4. $G^{2\nu}$ for ^{96}Zr, ^{100}Mo, and ^{116}Cd are calculated within the single-state dominance model (see Section 3).

"Two-Neutrino Double-Beta Decay", Ruben Saakyan, 10.1146/annurev-nucl-102711-094904

Isotope	Experiment	lifetime $T^{0\nu}_{\beta\beta}$ [years]
^{48}Ca	ELEGANT-VI	$> 1.4 \cdot 10^{22}$
^{76}Ge	Heidelberg-Moscow[14]	$> 1.9 \cdot 10^{25}$ [14]
^{76}Ge	GERDA	$> 1.8 \cdot 10^{26}$ [15]
^{76}Ge	MAJORANA	$> 8.3 \cdot 10^{25}$ [16]
^{82}Se	NEMO-3	$> 1.0 \cdot 10^{23}$
^{82}Se	CUPID-0	$> 4.6 \cdot 10^{24}$ [17]
^{96}Zr	NEMO-3	$> 9.2 \cdot 10^{21}$
^{100}Mo	NEMO-3	$> 2.1 \cdot 10^{25}$
^{116}Cd	Solotvina	$> 1.7 \cdot 10^{23}$
^{128}Te	CUORE	$> 3.6 \cdot 10^{24}$ [18]
^{130}Te	CUORE	$> 2.2 \cdot 10^{25}$
^{136}Xe	EXO	$> 3.5 \cdot 10^{25}$ [19]
^{136}Xe	KamLAND-Zen	$> 2.3 \cdot 10^{26}$ [20]
^{150}Nd	NEMO-3	$> 2.1 \cdot 10^{25}$

Поиск безнейтринного двойного бета-распада ^{96}Zr

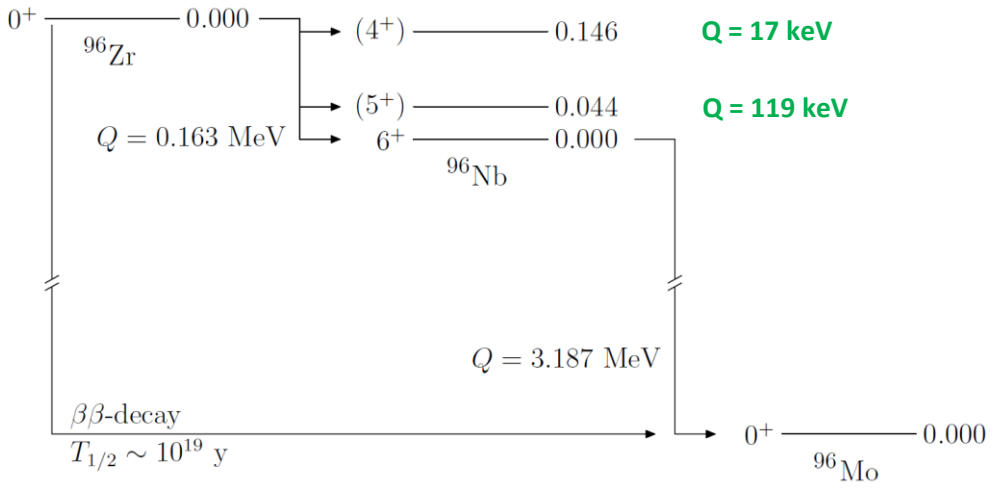
A. Leoncini MEDEX 2023

Объединенный институт ядерных исследований

Experiment	Transition	$T_{1/2}$ @ 90% C.L. (yr)	Ref.	Technique
ZICOS (Kamioka Observatory, Japan)	^{96}Zr → ^{96}Mo (g.s.)	under construction	[1]	Liquid scintillator
NEMO-3 (Frejus, France)	^{96}Zr → ^{96}Mo (g.s.)	> 9.2×10^{21} > 1.29×10^{22}	[2] [3]	Tracking detector
Kimballton Underground Research Facility, (USA)	^{96}Zr → ^{96}Mo (2^+_1)	> 3.1×10^{20}	[4]	HPGe
Collaboration at Frejus, (France)	^{96}Zr → ^{96}Mo (2^+_1, 0^+_1, 2^+_2, 2^+_3)	> (2.6 – 7.9) $\times10^{19}$	[5]	HPGe
Collaboration at LNGS	^{96}Zr → ^{96}Mo (2^+_1)	> 3.8×10^{19}	[6]	HPGe
Collaboration at LNGS	^{94}Zr → ^{94}Mo (2^+_1)	> 2.1×10^{20}	[7]	HPGe
TILES (TIFR, Mumbai)	^{94}Zr → ^{94}Mo (2^+_1)	> 5.2×10^{19}	[8]	HPGe
Kimballton Underground Research Facility (USA)	^{96}Zr → ^{96}Mo (6^+)	> 2.4×10^{19}	[9]	HPGe

β- и ββ-распады ^{96}Zr. Приведены энергия распада Q и некоторые возбужденные уровни ^{96}Nb

H Heiskanen, M T Mustonen and J Suhonen,
doi:10.1088/0954-3899/34/5/005



- $Q_{\beta\beta}$ = **3,35 МэВ**
- Интересен с теоретической точки зрения - $T_{1/2} \sim (Q_{\beta\beta})^5$
- Изотопная распространенность - **2,8 %**

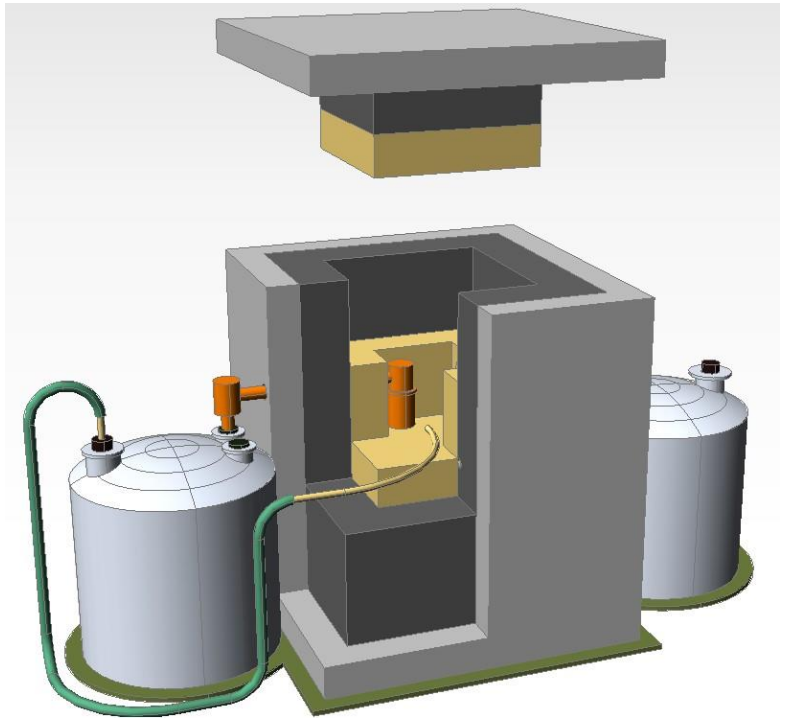
[1] EPS-HEP (2019) 437
[2] NPA 847 (2010) 168
[3] PhD U. Coll. London (2015)
[4] S.W. Finch et W. Tornow, Phys, Rev. C 92 (2015) 045501
[5] J. Phys. G: Nucl. Part. Phys. 22 (1996) 487
[6] C. Arpesella et al. Lett. 27 (l) (1994) 29
[7] E.Celi et al., Eur. Phys. J. C 83 (2023) 396
[8] N. Dokania et al. J. Phys. G: Nucl. Part. Phys. 45 (2018) 075104
[9] S.W. Finch, W. Tornow, Nucl. Inst. Meth. A 806 (2016) 70
[10] J. Heeck and W. Rodejohann, EPL 103 (2013) 32001

ПО ЭХЗ (Зеленогорск, Россия): крупнейший в мире завод по производству стабильных изотопов газоцентрифужным методом

Некоторые поставки ЭХЗ:
GERDA&MAJORANA: Ge-76 (до 200 кг)
CDEX (CJPL, Китай): Ge-76 (200 кг)
AMoRE: Mo-100 (более 120 кг)
EXO: Xe-136 (200 кг)
NEMO: Mo-100 (13 кг)
SuperNEMO: Se-82 (7кг)

Низкофоновый гамма-спектрометр «НИКА»

Detector	Ge-76
Type of crystal	Coaxial
Type of semiconductor	P-type
Mass, g	896
External diameter, mm	65
Height, mm	54
The thickness of the dead layer, mm	≈2
The effective mass, g	746
The wall thickness of the cryostat, mm	1
The ratio Peak / Compton (1332 keV)	45.4
The energy resolution, keV (1332 keV) at technical passport	2.18



Низкофоновая защита состоит из: 80 мм борированного полиэтилена, 230 мм свинца (Pb) и 120 мм меди (Cu).

Поиск безнейтринного двойного бета-распада ^{96}Zr

Search for neutrinoless double beta decay in $^{94,96}Zr$ isotopes using Cs_2ZrCl_6 crystal scintillators

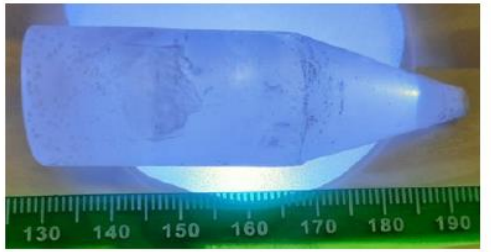
A. Leoncini [1,2], P. Belli [1,2], R. Bernabei [1,2], F. Cappella [3,4], V. Caracciolo [1,2], R. Cerulli [1,2], A. Incicchitti [3,4], M. Laubestein [5], V. Merlo [1,2], V. Nahorna [8], S. Nagorny [6,7], S. Nisi [5], P. Wang [8]

Some general properties	Cs_2ZrCl_6
Effective atomic number	46.6
Density (g/cm^3)	3.4
Melting point (°C)	850
Crystal structure	Cubic
Emission maximum (nm)	450 - 470
Scintillation time constants (μs)	0.4; 2.7; 12.5*
Light Yield	up to 41000 photons/MeV**
Linearity of the energy response	Excellent, down to 100 keV
Energy resolution (FWHM, %) @ 662 keV	3.5 - 7.0***
Pulse-shape discrimination ability	Excellent
Mass fraction of Zr (%)	16

* *for alpha events at room temperature (Dalton Trans. 2022, 51, 6944-6954)*
** *for gamma quanta at room temperature (article in press)*
*** *depends on the crystal quality, surface treatment and readout system*

Produced at Queen's University

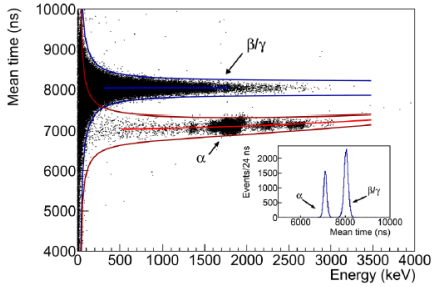
CsCl (99.9%) +
$ZrCl_4$ (99.9%) double sublimed
Bridgman growth technique

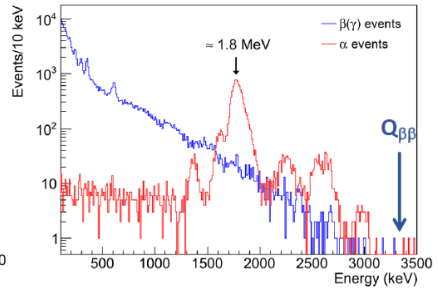


∅21.5×60 mm, about 60 g

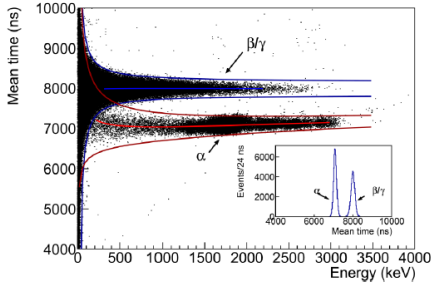
Pulse-shape discrimination and background α event selection

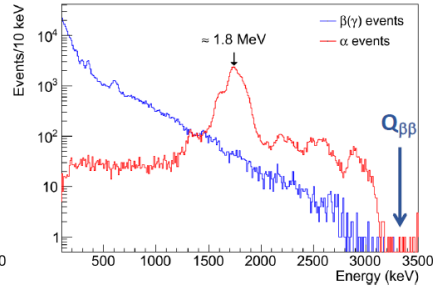
Cone
FoM = 7.8





Cylinder
FoM = 7.2

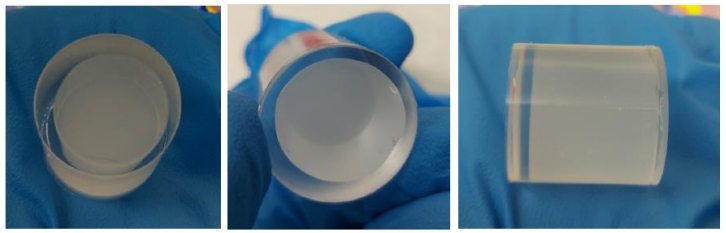




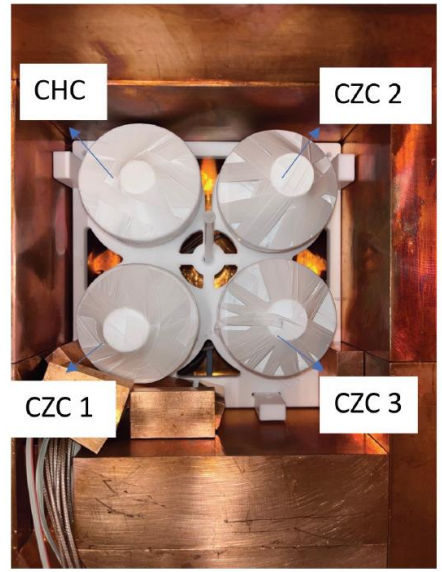
Selection efficiency is 99.7% in [0.1–3.5] MeV

Counting rate at ROI is 0.09 counts/(kg·keV·yr)

New low-background measurements in DAMA/CRYS setup (LNGS)



- Three new Cs_2ZrCl_6 crystals (more crystals are under production)
- Total mass = 59.5 g
- FWHM = 6-8% @ 662keV
- Produced from high purity and purified raw materials (> 99.99%)
- Crystals are encapsulated in a silicon-base resin + quartz window
- Modified experimental setup
- Measurements started in June 30th, 2023



Проект эксперимента ZICOS

ZICOS - Neutrinoless Double Beta Decay experiment using Zr-96 with an organic liquid scintillator -

Yoshiyuki FUKUDA[1], Shigetaka MORIYAMA[2][6], Katsuki HIRAIDE[2][6], Izumi OGAWA[3], Takahiro GUNJI[4], Ryohei HAYAMI[4], Satoru TSUKADA[4] and Shunsuke KUROSAWA[5]

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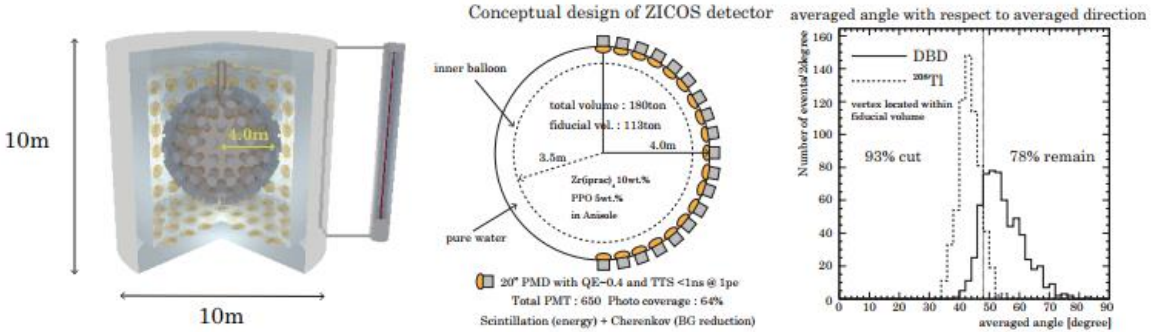
Abstract. A liquid scintillator containing a tetrakis(isopropyl acetoacetato)zirconium has been developed for ZICOS experiment. In order to reach the sensitivity $T^{0\nu}_{1/2} \geq 10^{27}$ years, we have to use tone scale of ^{96}Zr and have to reduce 95 % of backgrounds from ^{208}Tl decay, which should be major backgrounds observed around Q-value (3.35 MeV) of ^{96}Zr neutrinoless double beta decay. According to the Monte Carlo simulation, we demonstrated that new method using the topological information of Cherenkov light could reduce 93 % of ^{208}Tl background with 78 % efficiency for $0\nu\beta\beta$ signal. For an identification of Cherenkov light, the precise spectral pulse shape from both Cherenkov and scintillation was directly measured by using sub-MeV electrons from ^{90}Sr/^{90}Y beta source. The observed pulse rise and fall (decay) time for Cherenkov light were 0.8 ns and 2.5 ns, respectively. They were actually shorter than those times of scintillation light which were also measured by 1.6 ns and 6.5 ns, respectively. This clear difference of rise time will be used for the pulse shape discrimination in order to select photomultiplier tube which receives Cherenkov lights, and the topological information of Cherenkov light will be used for the reduction of backgrounds from ^{208}Tl decay.



Fabrication of Liquid Scintillators Loaded with 6-Phenylhexanoic Acid-Modified ZrO_2 Nanoparticles for Observation of Neutrinoless Double Beta Decay

Akito Watanabe [1,*], Arisa Magi [1], Akira Yoko [2], Gimyeong Seong [3], Takaaki Tomai [4], Tadafumi Adschiri [2,3,4], Yamato Hayashi [1], Masanori Koshimizu [1], Yutaka Fujimoto [1] and Keisuke Asai [1]

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Abstract: The observation of neutrinoless double beta decay is an important issue in nuclear and particle physics. The development of organic liquid scintillators with high transparency and a high concentration of the target isotope would be very useful for neutrinoless double beta decay experiments. Therefore, we propose a liquid scintillator loaded with metal oxide nanoparticles containing the target isotope. In this work, 6-phenylhexanoic acid-modified ZrO_2 nanoparticles, which contain ^{96}Zr as the target isotope, were synthesized under sub/supercritical hydrothermal conditions. The effects of the synthesis temperature on the formation and surface modification of the nanoparticles were investigated. Performing the synthesis at 250 and 300 °C resulted in the formation of nanoparticles with smaller particle sizes and higher surface modification densities than those prepared at 350 and 400 °C. The highest modification density (3.1 ± 0.2 molecules/nm^2) and Zr concentration of (0.33 ± 0.04 wt.%) were obtained at 300 °C. The surface-modified ZrO_2 nanoparticles were dispersed in a toluene-based liquid scintillator. The liquid scintillator was transparent to the scintillation wavelength, and a clear scintillation peak was confirmed by X-ray-induced radioluminescence spectroscopy. In conclusion, 6-phenylhexanoic acid-modified ZrO_2 nanoparticles synthesized at 300 °C are suitable for loading in liquid scintillators.

ЖС нагруженные металлами

ЖУРНАЛ НЕОРГАНИЧЕСКОЙ ХИМИИ, 2021, том 66, № 8, с. 1054–1062

ФИЗИКОХИМИЯ РАСТВОРОВ

УДК 546.662+546.682+546.657+546.831.4+539.1.074.6

β-ДИКЕТОНАТЫ И КАРБОКСИЛАТЫ МЕТАЛЛОВ (Gd, In, Nd, Zr) ДЛЯ СОЗДАНИЯ ЭЛЕМЕНТСОДЕРЖАЩИХ ЖИДКИХ ОРГАНИЧЕСКИХ СЦИНТИЛЛЯТОРОВ

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Поступила в редакцию 27.01.2021 г.
После доработки 13.03.2021 г.
Принята к публикации 15.03.2021 г.

Исследованы β-дикетонаты и карбоксилаты металлов с целью их использования для создания элементсодержащих жидких органических сцинтилляторов. Изучено их влияние на световыход и прозрачность сцинтилляторов. Приведены спектры поглощения β-дикетонатов неодима и циркония, а также 3,5,5-триметилгексаноатов неодима и гадолиния. Исходя из световыходов сцинтилляторов с введенными β-дикетонатами и карбоксилатами сделан вывод, что при больших концентрациях β-дикетонатов высокие значения световыхода (50%) могут быть получены только при введении значительных количеств сцинтилляционных добавок (вплоть до 100 г/л). Изучен вопрос стабильности металлсодержащих сцинтилляторов, связанный со структурой введенных соединений, глубиной очистки всех компонентов сцинтиллятора и влиянием карбоксилатов и β-дикетонатов металлов на окислительные процессы алкилбензолов.

ЖУРНАЛ НЕОРГАНИЧЕСКОЙ ХИМИИ, 2021, том 66, № 3, с. 1–7

ФИЗИКОХИМИЯ РАСТВОРОВ

УДК 546.831.4+547.442.3+539.1.074.9

β-ДИКЕТОНАТЫ ЦИРКОНИЯ ДЛЯ СОЗДАНИЯ Zr-СОДЕРЖАЩИХ ЖИДКИХ ОРГАНИЧЕСКИХ СЦИНТИЛЛЯТОРОВ

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Поступила в редакцию 10.06.2020 г.
После доработки 11.09.2020 г.
Принята к публикации 14.09.2020 г.

С целью создания низкофоновых Zr-содержащих жидких органических сцинтилляторов изучены β-дикетонаты циркония – синтезированный дипивалоилметанат и коммерчески доступный ацетилацетонат. Исследована их растворимость в органических растворителях – линейном алкилбензоле и псевдокумоле. Измерено поглощение света в псевдокумоле и гексане, а также световыход сцинтиллятора с введенными β-дикетонатами в зависимости от концентрации циркония и сцинтилляционных добавок. Показано, что световыход сцинтиллятора имеет высокое значение (>60%) только при малых концентрациях циркония (не более 2.5 г/л).

Оксид циркония ZrO_2, как кандидат

Scintillation Properties of Yttrium-stabilized Zirconia Crystals Synthesized by the Floating-zone Method

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(Received November 30, 2018; accepted March 25, 2019)

Keywords: scintillation, ZrO_2, single crystal, zirconia

We synthesized ZrO_2 and yittria-stabilized ZrO_2 crystals by the floating zone (FZ) method to evaluate their scintillation properties. Under excitation at around 250 nm, the photoluminescence (PL) emission peak appeared at around 450 nm. In the X-ray-induced scintillation spectra, an intense emission peak was also observed at around 450 nm in all the samples. The scintillation decay time profiles were approximated by a sum of two exponential decay functions, and the obtained value varied from 30–90 and 300–2230 ns depending on the composition.

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Nuclear Instruments and Methods in Physics Research A 537 (2005) 251–255

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Thin films of HfO_2 and ZrO_2 as potential scintillators

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Available online 25 August 2004

Abstract

Emission, excitation and absorption spectra of HfO_2 and ZrO_2 thin films grown by atomic layer deposition were investigated in the temperature range of 10-300 K. Time-resolved luminescence spectra were excited with a pulsed ArF laser and tuneable synchrotron radiation in UV–VUV. The strong emission with the peak position at 4.2–4.4 eV and with the decay time in μs range was revealed at 10 K in both materials. The emission was ascribed to the radiative decay of self-trapped excitons (STE). the features observed in the absorption and excitation spectra at 5.8 and 5.4 eV were most probably due to the formation of excitons; While the interband transitions started to dominate at 6.15 and 5.85 ev in HfO_2 and ZrO_2, respectively.

New Physics: Sae Mulli,
Vol. 63, No. 8, August 2013, pp. 939~944

DOI: 10.3938/NPSM.63.939

Structural and Optical Properties of AZrO$_3$ and AHfO$_3$ (A = Ca, Sr, and Ba)

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(Received 31 July 2013 : revised 6 August 2013 : accepted 9 August 2013)

We perform a systematic study on the physical properties of perovskite AZrO$_3$ and AHfO$_3$ (A = Ca, Sr, and Ba), which depend strongly on the size of the A ion. The 4d and the 5d band insulator compounds show similar structural and optical properties for a given A ion. From the X-ray diffraction and the Raman spectroscopy measurements, the crystal structures in both series of samples are clearly found to change from an orthorhombic to a cubic phase with increasing A-ion size. We estimate the optical bandgaps of the compounds by performing optical spectroscopy. In the photoluminescence measurement, we observe two visible emissions, one each near 420 and 500 nm, in AZrO$_3$ and AHfO$_3$, and their spectral weights are sensitive to the local distortion.

PACS numbers: 78.20.-e, 77.80.-e, 71.20.-b
Keywords: AZrO$_3$, AHfO$_3$, Structural property, Lattice dynamics, Optical spectroscopy, Photoluminescence

Scintillation and luminescence properties of undoped and europium-doped $CaZrO_3$ crystals

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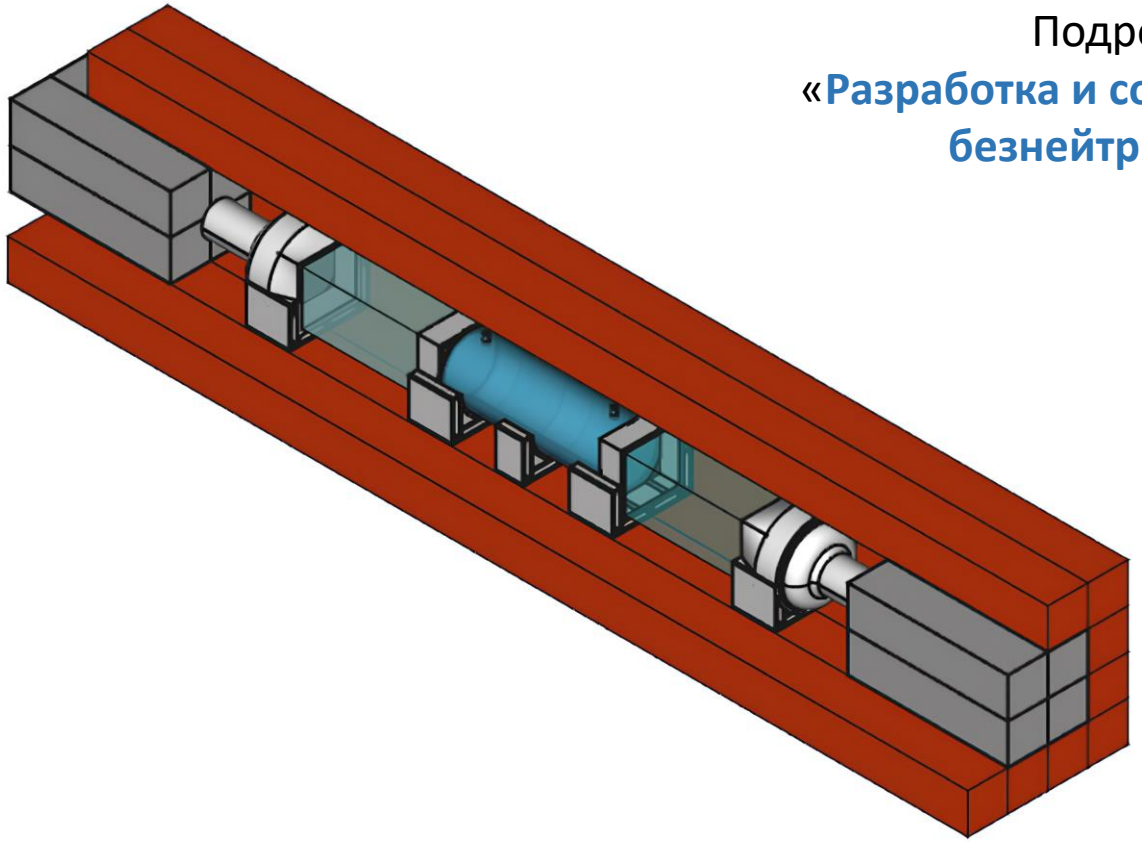
ABSTRACT

Undoped and Eu-doped $CaZrO_3$ crystals were synthesized by the xenon lamp floating zone method, and photoluminescence (PL) and scintillation properties were investigated. The undoped $CaZrO_3$ exhibited a broad PL spectrum peaking at around 410 nm while the Eu-doped $CaZrO_3$ showed some sharp emission lines due to 4f-4f transition of Eu^{3+}. The PL decay time constant of the undoped $CaZrO_3$ was 77.8 ns while the Eu-doped $CaZrO_3$ showed a typical value of 4f-4f transition of Eu^{3+}. In X-ray induced scintillation spectra, undoped $CaZrO_3$ showed a broad emission at 480 nm, and Eu-doped ones exhibited some emission lines at around 600 nm. The afterglow levels of the Eu-doped $CaZrO_3$ were lower than that of the undoped one.

Создание прототипа жидкосцинтилляционного детектора для поиска $0\nu\beta\beta$-распада ^{150}Nd

В качестве прототипа крупномасштабного детектора мы создаем детектор в рамках проекта "Новые методы исследования двойного бета-распада без использования нейтрино" (FZZR-2022-0004). Целью этого проекта является создание нового сцинтилляционного детектора для поиска безнейтринного двойного бета-распада в 150Nd, 96,94Zr, 176Yb.



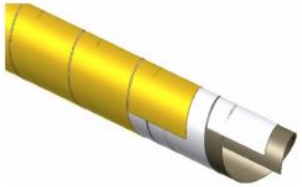
Подробнее в докладе А. В. Вересниковой
«**Разработка и создание прототипа детектора для регистрации безнейтринного двойного бета-распада Nd-150**»
20 Feb 2025, 13:45

Поиск редких процессов с помощью детектора на основе массива строутрубок

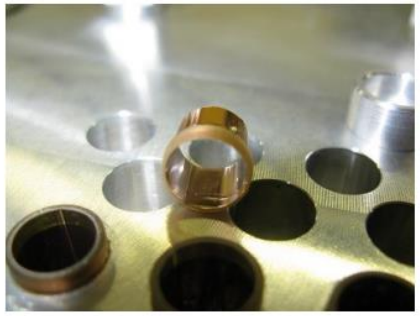
Объединенный институт ядерных исследований

Straw production

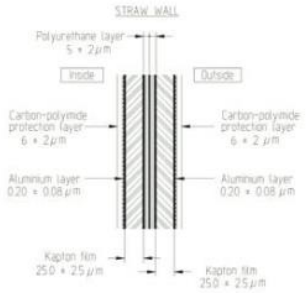
Glueing 2 overlapping strips (COMPASS)

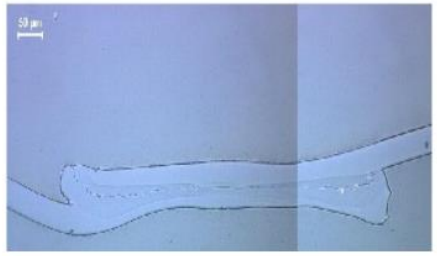


1 strip ultrasonically or thermally welded (NA62)



Glued and reinforced by carbon fibres (also improving cathode resistivity)





Signal formation

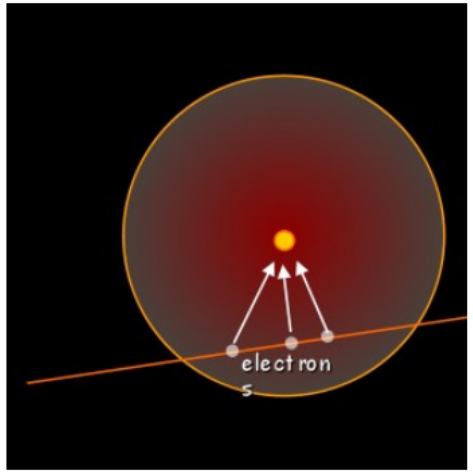
As any other proportional chamber

1/(t+t0) per cluster

!!DANGER!!

- This formula has been derived assuming constant mobility of ions (NOT velocity)
- The first 10ns -~100ns differ depending on gas and electric field
- The tail follows 1/(t+t0)
- The tail lasts until last ion arrival, can be ~100-s microseconds

With the characteristic shaping time of ~20ns, one uses only ~5% of total charge



https://indico.cern.ch/event/121649/attachments/68416/98147/straw.pdf

Изотопы кандидаты

$^{50}_{24}Cr_{26} \rightarrow {}^{50}_{22}Ti_{28}$ $^{54}_{26}Fe_{28} \rightarrow {}^{54}_{24}Cr_{30}$

$^{58}_{28}Ni_{30} \rightarrow {}^{58}_{26}Fe_{32}$ $^{60}_{30}Zn_{34} \rightarrow {}^{64}_{28}Ni_{36}$

Интересный кандидат для материала детектора
нержавеющая сталь, н-р марки **12Х18Н10Т**

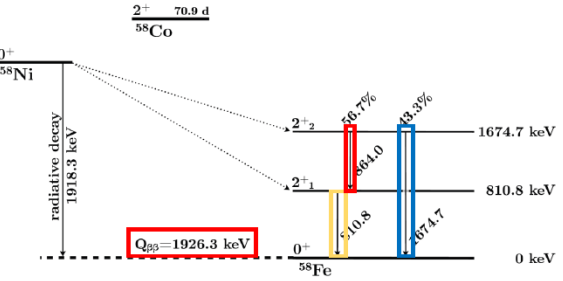
Химический состав – Cr-17-18%, Ni-9-11%, Ti-0,8%, Si – 0,8%, S-0,02%, Mn-2%, Cu-0,03%, P-0,035%, C0,12%, Fe~68%

Но, «стандартный» образец нержавеющей стали загрязнен U, Th, K-40, Космогенными изотопами

Солнечные адронные аксионы от ^{57}Fe – 14,4 кэВ

ECEC decay scheme of Ni-58

Ni-58 has one of the largest natural abundance among all double beta emitters – ~68,3%



Decay modes are feasible for investigation:

2νECEC: $^{58}Ni + 2e^- \rightarrow {}^{58}Fe(2_1^+) + 2\nu_e + 2X_{shell} + \gamma(810{,}8\ keV)$

2νECEC: $^{58}Ni + 2e^- \rightarrow {}^{58}Fe(2_2^+) + 2\nu_e + 2X_{shell} + \gamma(1674.8\ keV)$

$^{58}Ni + 2e^- \rightarrow {}^{58}Fe(2_2^+) + 2\nu_e + 2X_{shell} + \gamma(810.8\ keV) + \gamma(864.0\ keV)$

2νECβ^+: $^{58}Ni + e^- \rightarrow {}^{58}Fe(g.s.) + 2\nu_e + e^+ + X_{shell} + 2\gamma(511\ keV)$

0νECEC: $^{58}Ni + e^- \rightarrow {}^{58}Fe(g.s.) + \gamma_K + \gamma_L + \gamma(1918.3\ keV)$

The theoretical prediction for radiative 0ν$ECEC$:
$T_{1/2}$ ~ $2 \cdot 10^{35} \div 3 \cdot 10^{36}$ yr.

The theoretical prediction:

$T_{1/2}^{2\nu}\ (\beta^+EC, 0^+ \rightarrow 0^+) = 8.6 \cdot 10^{25}\ yr$

$T_{1/2}^{2\nu}\ (ECEC, 0^+ \rightarrow 2^+) = 6.1 \cdot 10^{24}\ yr$

arXiv: 9606023v1

Изотоп	γ - линия	Активность	$T_{1/2}$
Tl-208	2614,5 кэВ	(0,45±0,2) мБк/кг	**3 мин (1,9 года Th228)**
Bi-214	609 кэВ	(4,02±0,8) мБк/кг	**19,9 лет (1660 лет Ra-226)**
Cs-137	662 кэВ	(0,82±0,2) мБк/кг	**30,08 лет**
Co-58	810,75 кэВ	(1,6±0,23) мБк/кг	**70,86 дней**
Mn-54	834,85 кэВ	(4,5±0,4) мБк/кг	**312, 2 дней**
Ac-228	911 кэВ	(4,3±0,72) мБк/кг	**6,15 часов ($1{,}4 \cdot 10^{10}$ лет)**
Co-60	1332,5 кэВ	(4,8±0,4) мБк/кг	**1925,28 дней**
K-40	1460 кэВ	(11,2±3) мБк/кг	**$1{,}248 \cdot 10^9$ лет**

Спасибо за внимание!