EXAMINATION OF MULTI-LAYER SILICON DETECTOR IN MEASUREMENT OF ELECTRON SPECTRUM FOR BETA-DECAY OF ^{90}SR-^{90}Y

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Brief survey of recent achievements in investigations of nuclear beta decays is given with some emphasis on superallowed $0^+ \to 0^+$ Fermi transitions between $T=1$ nuclear states. Progress in construction of a detecting system for registration of electrons and positrons in studies of beta transitions is discussed. The spectra of electrons emitted in decay of ^{90}Sr and ^{90}Y nuclides are measured with the help of double-sided silicon detector. The spectra obtained are compared with results of computer simulation.

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1. INTRODUCTION

Researches into the phenomena caused by the charged weak currents, in particular the beta decays, are known to play an essential role in elaboration and advancement of the Electroweak Standard Model (SM). Review of investigations in this field can be found, for example, in Refs. [1-3].

Data on superallowed beta transitions among analog nuclear states with $T=1$ and $J^P=0^+$ are used [4-11] to verify the conserved vector current (CVC) hypothesis as well as to get value of the leading element in the quark mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix.

Up to now the highest precision for upper limit on the neutrino mass has been obtained in measurements of electron spectrum near its endpoint in tritium beta decay. The Troitsk and Mainz experiments (see [12] and references therein) result in $m_\nu < 2.05$ eV/c^2 and $m_\nu < 2.2$ eV/c^2, both at 95% confidence level (C.L.). Aim of the Karlsruhe Tritium Neutrino experiment (KATRIN) is to improve the sensitivities of the performed experiments and achieve upper limit $m_\nu < 0.35$ eV/c^2 [12,13]. Intensive theoretical and experimental efforts are made in recent years in order to gain deeper insight into origin of time-reversal-invariance non-conservation [14-22]. T-odd correlations in neutron and nuclear β-decays are analyzed with this end.

In experiment, being prepared by TRIμP collaboration at Kernfysisch Versneller Instituut in Groningen [20,21] (see also review paper [22]), the momenta of emitted beta particles and recoil nuclei are to be detected for decay of optically trapped isotopes of Neon and Sodium. The triple correlation between the spin of decaying nuclei (e.g., ^{19}Ne, ^{20,21}Na have $J^\pi=1/2^+$, 2^+, $3/2^+$ in the ground states) and the momenta of neutrino and positrons are planned to be inferred. Deviation of the measured expectation value for the correlation from zero could serve as a clear indication for violation of time reversal symmetry.

The above-mentioned directions of investigations have high priority in modern scientific programs in the area of fundamental nuclear physics [23-25]. As is stressed [1-11, 22-25], both calculations and measurements have to provide reliable treatment of the processes and the observables to contribute in severe testing the SM and searching effects that may be induced by interactions beyond it.

In Sect. 2 of the report we present cursory overview of some results, obtained in recent studies of superallowed Fermi transitions. This section aims to demonstrate high importance of experiments on nuclear beta decays, that involve 0^+ states belonging to isotriplet of nuclei, for theory of charged weak interactions. The current status in development of the detecting system that can be used to measure the energy spectra of beta particles is discussed in Sect. 3. In the last section, we draw attention at decays of positron emitters Carbon-11, Nitrogen-13, Oxygen-15, Fluorine-18 as a tool for studying properties of unstable nuclei.

2. ADVANCES IN INVESTIGATIONS OF SUPERALLOWED BETA DECAY

Zero component of the vector charged current is known [3] to contribute to the amplitude of superallowed beta transitions between nuclear states of the same isospin multiplet with $J^P=0^+$. The nuclear matrix elements for these transitions can be cast into a form when they are proportional to the weak coupling constant for leptonic muon decay and up-down element of the CKM matrix [3-11]. In the approximation where the isospin symmetry is exact, the rate of the transitions is not affected by any details of nuclear structure.

One can hope that the ft-values deduced from the experimental data for different superallowed Fermi transitions that involve 0^+ analog nuclear states with $T=1$ are not significantly influenced by nuclear environment. Nevertheless, measurements with precision to ±0.1% or better for nine nuclei from ^{10}C to ^{54}Co yield average $\overline{ft}$=3043.9(6) sec. with chi-square per degree of freedom $\chi^2/\nu=6.38$ [4,6].

Treatment [4,5,7,9,10] of the isospin-symmetry-breaking and radiative corrections leads to the "corrected" ft-value denoted by $\mathcal{F}t$. The nucleus-dependent

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terms are included in this quantity. The size of the corrections turns out to be about one percent.

Average value for the twelve most precise measurements (with accuracy better than 0.4%) is $\overline{\square t}$ =3072.7(8) sec. with χ^2/ν=0.42 [9,10]. The nuclei from A=10 to A=74 are considered in this case. The universality for lepton and quark charged currents and CVC hypothesis is confirmed. Among other implications it worth to mention strict constraints imposed on the scalar currents by the results [9,10].

The obtained value $|V_{ud}|$=0.9738(4) together with V_{us} and V_{ub} recommended by PDG [26] allow one to arrive at the conclusion that unitarity relation for the first row of the CKM matrix is violated by 2.4 standard deviations. At the same time, the sum of the top-row elements squared $\sum_{i=d,s,b}|V_{ui}|^2$ meets unity and this unitarity condition is almost perfectly satisfied [9,10] (see also [11]) when the value for $|V_{us}|$ is taken according to the results of recent experiment E865 at Brookhaven. The branching ratio for K^+_{e3} decay $K^+ \to \pi^0 e^+ \nu_e$ has been measured in E865.

As is seen from the above discussion, both experiments on the superallowed beta decays and analysis of the transitions, making use of methods developed in studies on nuclear structure, give important information for theory of charged weak interaction.

3. DEVELOPMENT OF DETECTORS FOR STUDYING NUCLEAR BETA DECAYS

3.1. SPECTRA OF ELECTRONS EMITTED BY ^{90}Sr-^{90}Y SOURCE

The present paper carries on studies [29,30] of the spectra of ionization losses for electrons radiated from ^{90}Sr-^{90}Y source. Nuclides Strontium-90 and Yttrium-90 are known to be pure beta emitters and decay with half-life $T_{1/2}$ = 28.79 years and 64.10 hours [28] (cf. [30]). The nuclear states involved in the transitions $^{90}Sr \to {}^{90}Y e^- \bar{\nu}_e$ and $^{90}Y \to {}^{90}Zr e^- \bar{\nu}_e$ have $J^P = 0^+$, 2^- and 0^+, respectively.

The measurements are performed with an assembly that consists of two silicon diodes with an absorbent between them (see Fig. 1). The signals from the diodes D1 and D2 are amplified by the preamplifiers PA and by the amplifiers AF1 and AF2. Peaking time of AF1 (AF2) is 1.5 (0.25) mcs. The signal from AF1 is received by analog-digital converter ADC controlled externally.

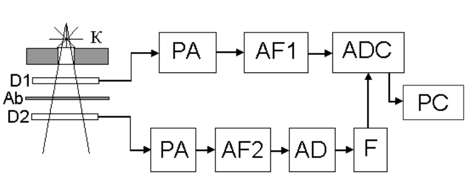

Fig. 1. *Scheme of the experiment. ^{90}Sr-^{90}Y source is placed at the top of the collimator K. D1 and D2 are silicon detectors, Ab is an absorbent*

With the help of amplitude discriminator AD and shaper F the signal from AF2 is converted to a standard rectangular pulse that is suitable for external ADC triggering. The discrimination level is fixed after the measurement of the pulse spectrum at exit of the amplifier AF2. The delay for triggering pulse is determined by the shape of the spectra obtained after series of measurement. For a pair of detectors with size of active area 6.5x6.5 mm^2 and 2x2 mm^2 operating in the fast pulse coincidence mode the resolving time has been found to be 70 ns and 30 ns, respectively.

Spectra of energy losses measured by the first detector are presented in the top panel of Fig. 2.

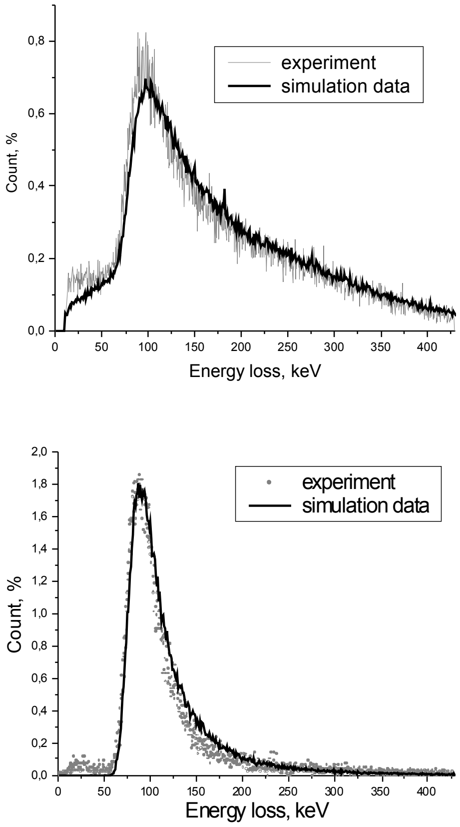

Fig. 2*. The spectra of energy losses in the detector D1. Top (bottom) panel corresponds to the operating mode without (with) triggering D1 from the detector D2*

As is seen from the Fig. 2 exact determination of the peak position is hardly possible. Really, the incoming electrons pass through the detector at different angles and have different lengths of the paths inside the detector. Thus, for a detector with thickness of 0.3 mm the distribution has smooth maximum at 90…100 keV. The most probable value of the electron energy loss is found to be 95 keV.

The electrons passed through the first detector and the absorbent are detected by second detector. The energy losses in the first detector are measured when they exceed 60 keV. The second detector reveals about 10% of events fixed in the first detector. As it was expected, the spectrum measured by the second detector has a sharp peak (see bottom panels in Fig. 2). Maximum value is reached when the energy loss is about 89 keV.

It is should be noted that no visible variations in the spectrum shape have been found within the energy interval examined. This observation is in correspondence with general properties of energy loss spectra due to ionization [26]. At energies of emitted electrons below 500 keV multiple scattering can considerably affects the spectra. However, the position of the peak is not influenced by these effects.

3.2. COMPUTER SIMULATION OF DETECTING SYSTEMS

Along with the data obtained Fig. 2 shows the results of the computer simulations for spectra of energy losses. It is assumed that the ^{90}Sr-^{90}Y source has the form of a circle and the electrons are emitted form any point of it at arbitrary direction with equal probability. The arrangement of the collimator and the target consisted of two silicon detectors with an aluminum absorbent placed between them is displayed in Fig. 3.

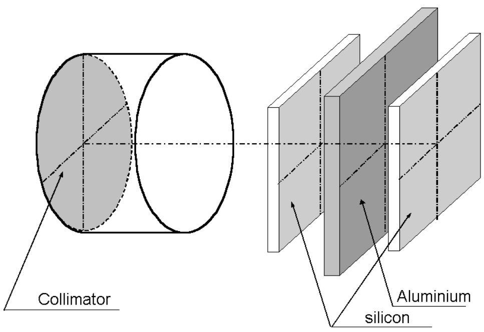

Fig. 3. *Detector geometry used in the simulation*

The detector assembly operates in the coincidence mode. Signals from the detectors are processed by the adder triggered by the coincidence system.

The spectra of energy losses have been simulated with the help of Geant 3.21 taking into account ionization, multiple scattering, bremsstrahlung, etc. The energy of outgoing electrons may vary from zero up to the end-point energy W_0=2283 keV [28] for the ^{90}Y beta-decay spectrum. In the case of ^{90}Sr decay W_0=546 keV.

One can conclude from Fig. 2 that the results of the measurements and of the computer simulations agree satisfactory. Success of the calculations performed provides grounds for carrying out restoration of the beta-spectrum for the source.

We assume that electrons pass through the collimator with diameter 2 mm and length 5 mm and interact with the assembly of the silicon detectors. The assembly contains up to 10 detectors with size 6,5x6,5x0,3 mm^3 placed closely. The centers of the silicon plates are on the same axis.

Fig. 4 shows, that in the case when the detector has thickness 1 mm, the peak is observed at energy about 350 keV. This peak corresponds to the most probable energy losses of an electron with initial energy more than 1 MeV. For thickness 2 mm the peak is less pronounced. Calculations carried out allow one to conclude that electrons from ^{90}Sr-^{90}Y source are detected by 3 mm of silicon assembly (e.g., by 10 detectors with thickness of 300 micron) at 98% C.L.

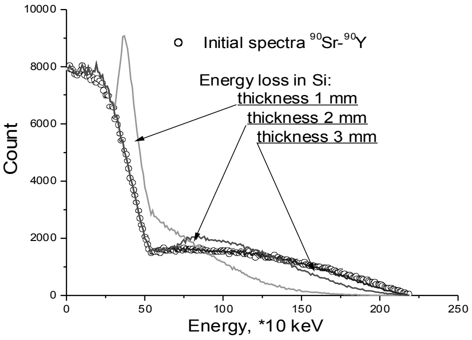

Fig. 4. *Dependence of the obtained β-spectra on the thickness of the detector assembly*

As demonstrated in Fig. 5, the energy loss spectrum, obtained from data [28] (circles), coincides with results of simulations for 3 mm detector assembly.

The spectrum of electrons radiated from ^{90}Sr-^{90}Y source is a sum of the beta decay spectra for ^{90}Sr and ^{90}Y shown separately in Fig. 5.

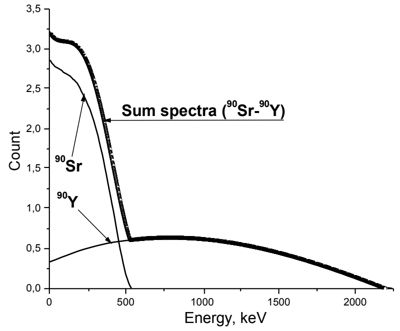

Fig. 5. *Spectrum of electrons emitted from the ^{90}Sr-^{90}Y source (circles) [28]*

4. DISCUSSION AND OUTLOOK

In this report, we have described the multilayer detecting system constructed from single-channel planar and multichannel microstrip detectors [31] that is being elaborated at NSC KIPT. Results of measurements and simulations of electron spectra for the beta decays of ^{90}Sr and ^{90}Y nuclides are presented. It is demonstrated that the detecting system can be optimized for exploitation in beta-decay experiments. Thus, the detector thickness can be increased to improve the energy resolution. Additional enhancement of the performance may be achieved by of cooling down the detector.

Below we also discuss the beta decay of $^{7}_{4}\mathrm{Be}$. The decay mode for $^{7}_{4}\mathrm{Be}$ is the electron capture with half life 53.29 d. Spin and parity of the nuclides do not change in the decays of $^{7}_{4}\mathrm{Be}$, $^{11}_{6}\mathrm{C}$, $^{13}_{7}\mathrm{N}$ and $^{15}_{8}\mathrm{O}$. For $^{7}_{4}\mathrm{Be}$, $^{7}_{3}\mathrm{Li}$, $^{11}_{6}\mathrm{C}$ and $^{11}_{5}\mathrm{B}$ one has $J^P = 3/2^-$, and $J^P = 1/2^-$ for $^{13}_{7}\mathrm{N}$, $^{13}_{6}\mathrm{C}$, $^{15}_{8}\mathrm{O}$ and $^{15}_{7}\mathrm{N}$. The decay $^{18}_{9}F \to {}^{18}_{8}Oe^{+}\nu_e$ corresponds to the transition $1^+ \to 0^+$.

The measurements carried out in the report give some grounds for asserting that the detecting systems can be used in studies of beta transitions, specifically ones given in the table.

Properties of positron emitters with Z=6…9 and half life that exceeds 2 min

Initial state	Half life	Final state	β^+-Decay energy
${}^{11}_{6}C$	20.39 min	${}^{11}_{5}B$	0.960 MeV
${}^{13}_{7}N$	9.965 min	${}^{13}_{6}C$	1.198 MeV
${}^{15}_{8}O$	122.24 sec.	${}^{15}_{7}N$	1.732 MeV
${}^{18}_{9}F$	109.77 min	${}^{18}_{8}O$	0.634 MeV

As is seen from the table, the decay energy for the transitions takes on values that allow measuring the positron spectra with the help of the detectors elaborated. Note, that radioactive isotopes ${}^{11}C$, ${}^{13}N$, ${}^{15}O$ and ${}^{18}F$ are utilized in positron emission tomography. The superallowed beta decays of ${}^{7}Be$ and ${}^{11}C$ are demonstrated to be a sensitive testing ground for advanced *ab initio* calculations aiming to explain properties of the light nuclei using realistic models of internuclear forces.

The Gamov-Teller transitions (GTT) from ${}^{7}Be$ ground state (g.s.) to the g.s. and the first excited states of ${}^{7}Li$ have been studied in [32] and [33]. The Green's function Monte Carlo method [32] and no-core shell model [33] are employed to obtain the nuclear wave functions (WFs) the matrix element depends on. Calculations [32] and [33] with Argonne AV18 and AV8' nucleon-nucleon potentials in junction with Urbana-IX and Tucson-Melbourne TM'(99) three-nucleon interaction (TNI), respectively, show that inclusion of TNI leads to a clear improvement in description of experimental data on the strengths B(GT) of GTT. It should be stressed that B(GT) for transitions between the ground states of the nuclides is deduced from beta-decay experiment.

Calculations [33] with two-nucleon effective interaction derived from AV8' NN-potential predict incorrect g.s. properties, e.g. spin, for ${}^{11}C$. Inclusion of TM'(99) TNI in addition to AV8' results in effective internucleon forces that provide much better description on the energy spectra than in the case of effective interaction obtained from AV8' NN-potential along.

Transitions from g.s. of ${}^{11}B$ to states of ${}^{11}C$ with the excitation energy up to E_x=8.420 MeV ($J^P=5/2^-$) have been explored in [33] as well. The GTT strength B(GT) for ${}^{11}B \rightarrow {}^{11}C$ has proved to be strongly affected by TNI. Modifications of the nuclear WFs due the TNI reduce to a large extent discrepancies between the results of the calculations and the B(GT) values from beta-decay measurements for the g.s. to g.s. transition, and for E_x>0 from ${}^{11}B(p,n){}^{11}C$ and ${}^{11}B({}^{3}He,t){}^{11}C$ experiments [34,35].

Thus, new data on the beta transitions displayed in the table, in particular for Nitrogen, Oxygen and Fluorine, would be of interest for studying properties of unstable nuclei and investigation of potentialities of *ab initio* methods [32, 33] in theory of nuclear structure.

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ТЕСТИРОВАНИЕ МНОГОСЛОЙНОГО КРЕМНИЕВОГО ДЕТЕКТОРА В ИЗМЕРЕНИЯХ СПЕКТРОВ ЭЛЕКТРОНОВ В БЕТА-РАСПАДАХ ЯДЕР ^{90}SR-^{90}Y

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В докладе кратко обсуждаются достижения в недавних исследованиях бета-распадов атомных ядер. Основное внимание уделяется сверхразрешенным $0^{+}\to 0^{+}$ переходам Ферми между ядерными состояниями с изоспином *T=1*. Выполнены измерения спектра электронов, испускаемых в распадах ядер стронция-90 и иттрия-90, с помощью разрабатываемого двухстороннего кремниевого детектора. Полученные спектры сравниваются с результатами компьютерного моделирования.

ТЕСТУВАННЯ БАГАТОШАРОВОГО КРЕМНІЄВОГО ДЕТЕКТОРА У ВИМІРАХ СПЕКТРІВ ЕЛЕКТРОНІВ У БЕТА-РОЗПАДАХ ЯДЕР ^{90}Sr-^{90}Y

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У доповіді коротко обговорюються досягнення в недавніх дослідженнях бета-розпадів атомних ядер. Основна увага приділяється понаддозволеним $0^+ \rightarrow 0^+$ переходам Фермі між ядерними станами з ізотопічим спіном, що дорівнює одиниці. Виконано виміри спектрів електронів, що випускаються в розпадах ядер ^{90}SR та ^{90}Y, за допомогою розроблювального двостороннього кремнієвого детектора. Отримані спектри порівнюються з результатами комп'ютерного моделювання.