

# Application of electron spectroscopy for studying inverse $\beta$ -decay at increasing density of neutrino flux due to diffraction

V.A. Trapeznikov<sup>1,2</sup>, I.N. Shabanova<sup>1,2</sup>, V.A. Zhuravlev<sup>1</sup>

<sup>1</sup>*Udmurt State University, Izhevsk, Russia*

<sup>2</sup>*Physicotechnical Institute, Ural Branch of RAS, Izhevsk, Russia,*

*E-mail: xps@fli.udm.ru*

## Abstract

In the present paper, a new method is substantiated for studying the inverse  $\beta$ -decay with the use of Auger- and photoelectron spectra for the registration of electrons, which appear at the interaction of low-energy ( $\sim 1$  MeV and smaller) electron neutrinos ( $\nu_e$ ) with a substance. The new method is an alternative to the existing method based on the use of high-energy  $\nu_e$  with the energy of  $\sim 10$  MeV, which form electrons at the interaction with a substance, the energy of which is sufficient for Cherenkov effect to appear. The offered method was realized using a high-sensitive electron magnetic spectrometer with double focusing by a non-uniform magnetic field  $\pi\sqrt{2}$  with the cyclotron orbit radius of 100 cm, which was built at our institute; the first x-ray electron spectra were obtained on it and the constant of the device was determined.

**Key words:** *inverse  $\beta$ -decay, Cherenkov effect, neutrino detector, neutrino polarization, cross-section of neutrino and substance interaction, 100-cm electron magnetic spectrometer, focal plane, quadrupole lens, electron spectra, device constant.*

The studies of the inverse  $\beta$ -decay are characterized by a very small cross-section of the interaction of neutrinos with a substance,  $\sim 10^{-43}$ . Naturally, it imposes stricter requirements to the sensitivity of the instruments used for the registration of the interactions, which results in huge sizes of detectors. Thus, in the case of studying the inverse  $\beta$ -decay on the device Superkamiokande (Japan) [1], the neutrino detector is a reservoir containing 50 thousand tons of fluorescent liquid and thousands of Cerenkov's counters immersed in the reservoir, which record the tracks of electrons formed as the result of the interaction of the high-energy neutrino flux with the liquid. Another device for recording neutrino flux, which is based on the submarine neutrino detector and uses sea-water, requires a significant amount of sea-water that is estimated at  $1\text{ km}^3$  [2].

For the inverse  $\beta$ -decay  $\nu_e + d \rightarrow p + p + e^-$  by the charge current (CC), the use of an electron spectroscopy method for recording electron fragments resulting from the interaction of low-energy  $\nu_{e,l}$  with a substance is more efficient in comparison with the registration of Cerenkov's electrons using high-energy  $\nu_{e,h}$ , the amount of which is four orders of magnitude smaller than that of low-energy  $\nu_{e,l}$  in the range from 1 to 10 MeV [3]. In addition, the excitation of the electron system by low-energy  $\nu_{e,l}$  is by several orders of magnitude more efficient than the excitation by high-energy  $\nu_{e,h}$  since high-energy particles with  $\sim$ MeV energies exceed by several orders of magnitude the potential of  $\sim$ KeV of the electron system excitation.

When the electron system is excited by low-energy  $\nu_{e,l}$ , in the case of the  $\nu_{e,l}$  interaction with the detector substance, consisting of the atoms with a large atomic number  $Z$ , the total pulse resulting from the ensemble of Auger-electrons of the detector system will significantly (per number of Auger-transitions in the excited system) exceed the number of electrons recorded by the system for high-energy  $\nu_{e,h}$ , where only one Cerenkov electron is recorded per one interaction. The entire ensemble of Auger-transitions will take place in the case of high-energy

$\nu_{e,h}$  as well, however, Auger-electrons have much smaller energy than that which is necessary for producing Cherenkov effect, consequently they are not registered by Cherenkov's counters.

The inverse  $\beta$ -decay allows to solve actual problems in the sphere of practical use of neutrinos: evaluation of the power of a reactor, the variation of the composition of the fissile region, etc. [4]. Here the information carrier is the density of states of neutrinos from the energy  $N_{\bar{\nu}_e}(E)$ ; the hypothesis on the difference in the  $\nu_e$  spectra obtained from the fission products of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  was first suggested at the Institute of Atomic Energy (Russia) [5] and it was experimentally confirmed [6]. The method can be used for the evaluation the operation regime of a reactor (the evaluation of the reactor power; the amount of the plutonium used, etc.).

In the present work, the use of the electron spectroscopy method for the solution of the problems similar to those of nuclear physics is considered because the method is more available and more accurate since the density of the electron states  $N_e(E)$  is dependent of the electrons in the range of energies much smaller (by orders of magnitude) than the energies in the range corresponding to the density of states of electron neutrinos  $N_{\nu_e}(E)$ , which results in better resolution, and finally in significantly smaller cost. Large resolution of the method of electron spectroscopy of  $N_e(E)$  in contrast to the neutrino method for the evaluation of the density of states of  $N_{\nu_e}(E)$  allows to increase the effectiveness of the signal detection from the reactor when the distance is increased.

It is of interest to evaluate the possibilities of the use of linearly polarized low-energy electron neutrinos for the identification of neutrino signals coming from different sources. By analogy with the x-ray linear polarization, in which the diffraction is obtained with the use of crystals at Bragg-Wulf angle of  $45^\circ$  depending on the interplanar spacing, the neutrino energy is determined unambiguously according to Bragg-Wulf equation

$$n\lambda = 2d \sin\theta,$$

where  $n$  is the order of reflection,  $\lambda$  is the length of neutrino wave,  $d$  is the interplanar spacing in a crystal, and  $\theta$  is the reflection angle.

For example, when an aluminum crystal is used, which has the maximal intensity of reflection of 140 from the octahedron plane (III), at  $d = 2.33$  and the angle sine  $45^\circ$  the neutrino energy is 3.7 keV. When tritium is selected as the neutrino source, the electrons formed at the  $\beta$ -decay will have the energy of 14.9 eV, since the maximal energy of neutrinos is 18.6 keV.

For recording neutrino flux from the Sun, nuclear reactors and other sources [7] it is offered to use a supersensitive electron magnetic spectrometer with double focusing by non-uniform magnetic field  $\pi\sqrt{2}$  [4]. The spectrometer was first used by K. Seigbahn and K. Edvardson at the University in Uppsala; it has the largest possible radius of the cyclotron orbit as the sensitivity of such instruments varies proportionally with the square of the radius. The selection of focusing in our device, which can simultaneously register electrons of different energies due to the presence of the focal plane, makes it possible to use the set of micro-channel plates without limiting the number of channels, which is important for increasing the sensitivity of the device.

One of the largest in the world [8] electron iron-free magnetic spectrometer with double focusing by non-uniform magnetic field  $\pi\sqrt{2}$  with the radius of the cyclotron orbit of 100 cm (see the Fig. 2) was developed and built by mutual efforts of the Udmurt State University and Physicotechnical Institute of the Ural Branch, RAS. The interval of the spectra studied is from 100 eV to 4 MeV. [9].

The direct detector of neutrinos is a chamber containing lead oxide in the superconducting state, which is necessary for increasing the length of the free path of the excited electrons and due to this their number registered by the spectrometer also increases, since the electrons appearing as the result of the  $\nu_e$  interaction with lead are directed by the quadrupole lens to the slit of the electron spectrometer. The quadrupole lens was designed at the Institute of Analytical Instrument-making of RAS [10]. The electron detector is a micro-channel plate produced by the company "Baspic", Vladikavkaz, Russia. When polarized neutrinos are used, a crystal holder with the crystal bending according to Johann [11] is placed in front of the chamber (Fig. 3a) for the case when the radiation is coming from the outside of the focal circle [12] (Fig. 3b) and for the case with neutrinos as in work (Fig.4)[13].

The spectrometer can rotate over the axis perpendicular to the plane of the magnetic meridian, which leads to the width dependence and allows to take into account the angle of ecliptic at investigating solar anti-neutrino flux in the daytime and at night. In addition to the neutrino processes, it is possible to investigate fast processes using the device, for example, to investigate surface layers of solids for one impulse of impact load lasting for  $10^{-5}$  s. Small time of the registration of photoelectrons allows to investigate the electronic structure of the surface of components of machines and mechanisms operating in cyclic mode (compressor and turbine blades, air-engines, gascompressor units, valves, rings and cylinders of internal-combustion engines, springs, barrels of automatic guns, teeth of cutters and gear cutters, etc.) during one cycle. The device provides the possibility to investigate short-lived free radicals, which is important for understanding biological processes at the molecular and atomic levels. Some problems were refined in connection with new data received on the investigation of electron spectra of small doses of radiation [14]. We believe that the task discussed in the present paper concerning the application of the electron spectroscopy for studying the inverse  $\beta$ -decay is rather new, since neither in the keynote article of D.A. Shirley, B.L. Peterson, M.P. Howels "Electron spectroscopy in the 21<sup>st</sup> century" nor in the review [16] nothing is mentioned of such statement of the task [12].

The experiment on obtaining electron spectra, which reflect the density of states of  $\nu_e$ , consists of three successive steps:

- 1) The whole spectrum, which fits into the aperture of the microchannel plates occupying the entire plane of the spectrometer, and the channels of which are connected to one anode, which will show that there is the interaction of neutrinos with the detector substance;
- 2) The set of channels of the microchannel plates is divided into equal amounts, which are intended for equal energy parts of the focal plane, and each group of channels is connected to a separate anode; this will show a rough spectrum of the distribution of the neutrino density of states by energy, and finally;
- 3) The partition of each large region of channels into narrow spectral intervals with a separate anode for each of them in order to reveal the fine structure of the neutrino spectrum. It is necessary to note that in all the cases the whole spectrum will be obtained simultaneously. On the spectra under study, the variation of the neutrino density of states will be reflected in the process of the variation of the neutrino radiation mode in time or during the variation of either the distance or the angle dependence between the neutrino source and the electron spectrometer.

## Conclusion

In the present paper, a scheme of a device is offered allowing to increase the density of neutrino flux, wherein diffraction on a bent crystal is used, which allows to increase the density of the total neutrino flux by an order of magnitude.

A brief description of the main components of the 100-cm electron magnetic spectrometer is given, which has a focal plane, the rotation axis of an energy analyzer that is perpendicular to the magnetic meridian plane. The first Auger- and photoelectron spectra are obtained. The constant of the instrument is determined equal to  $c = 0.4 \text{ gauss*cm/mA}$ . Initial projects have been programmed.

A scheme of a device is offered allowing to increase the neutrino flux density due to the diffraction on bent crystals, the number of which can be considerable, and each crystal can be of the size as large as possible, which allows to increase the density of the total neutrino flux by 9 – 10 orders of magnitude. The device can be used as a neutrino telescope. The general task of the present investigation on the increasing of the neutrino flux density is obtaining of a new source of restorable energy, i.e. neutrino energy.

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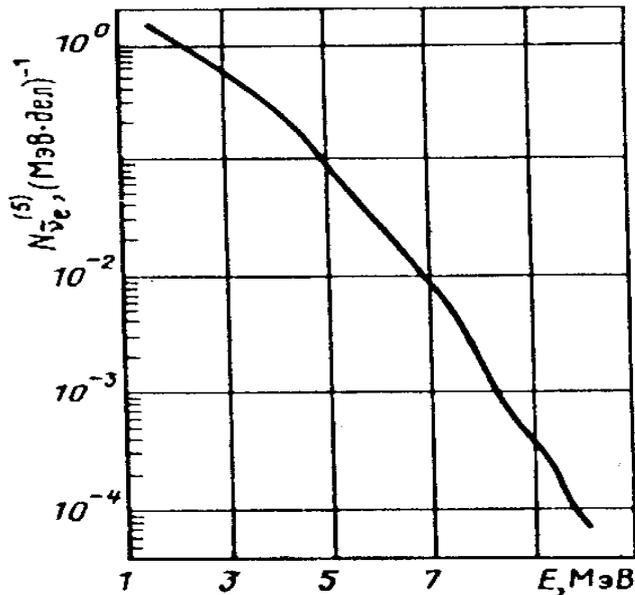


Fig.1. An anti-neutrino spectrum from fission fragments of  $^{235}\text{U}$  [3].



Fig.2. The 100-cm electron spectrometer (front view).

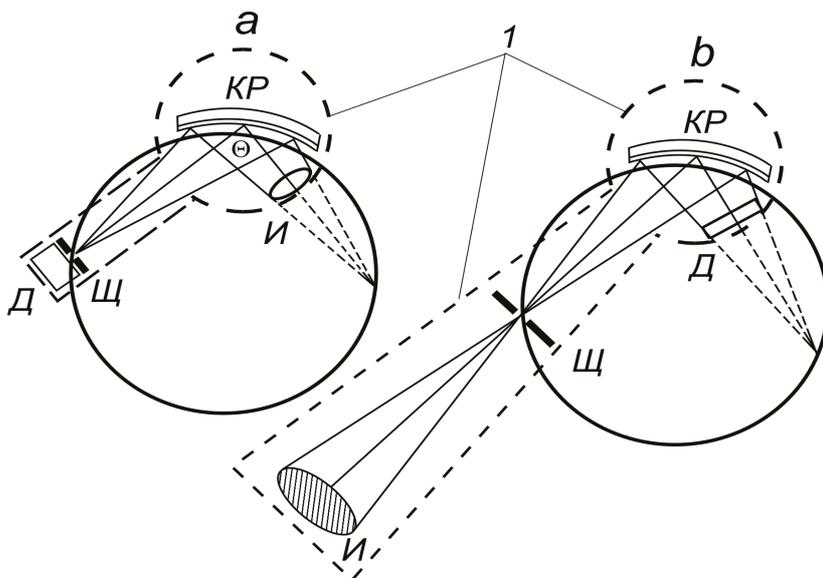


Fig.3. The scheme of the x-ray path according to Johann method:

- a) a normal variant: D is a detector, S is a slit, CR is a crystal, S is a radiation source,
- b) the variant with an x-ray generator placed outside the focal circle of the path of rays according to Johann method.

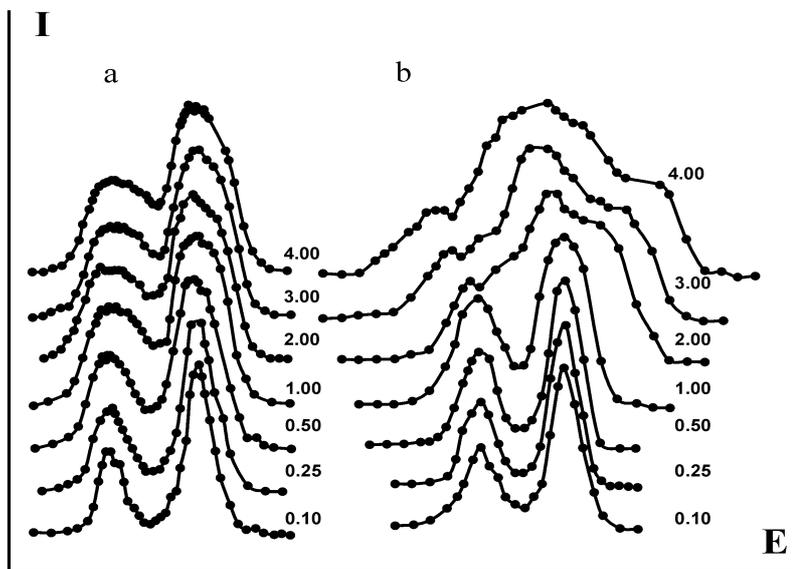


Fig.4.  $K\alpha_{1,2}$ -spectra of Co obtained with the use of the inverted scheme:

- a) primary spectra
- b) secondary spectra