Measurement of the spectrum of the internal bremsstrahlung from $^{51}$Cr

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Abstract. The activity of the intense artificial neutrino source in the experiment BEST will be determined by measuring of the internal bremsstrahlung (IB) spectrum from $^{51}$Cr. The paper describes the measurements of the IB spectrum from unsealed point-like $^{51}$Cr source using spectrum recovery method, and the main sources of uncertainties are discussed.

1. Introduction

Intense artificial neutrino sources based on the $\beta$-decay isotopes produced by neutron irradiation in high-flux nuclear power reactors are a convenient tool for studies of low-energy neutrinos. $^{51}$Cr and $^{37}$Ar sources were used by the SAGE [1, 2] and GALLEX [3, 4] experiments for calibrations of their solar neutrinos gallium detectors. Currently in the Baksan neutrino observatory of INR RAS the experiment BEST, in which a gallium target of the SAGE detector, divided into two zones, will be irradiated by monoenergetic neutrinos from 3 MCi $^{51}$Cr source, is prepared. The experiment is aimed at searching of short baseline oscillation and determination of the oscillations parameters [5].

In the BEST experiment the neutrino source activity will be determined by two independent methods, one of which is through measuring of IB spectrum, comparing the measured spectrum with the spectrum of the photons in the source [6]. The method allows obtain the value of the source activity for unevenly distributed activity through the volume of the source.

In order to measure the activity of the source by spectrometric method with the required accuracy ($\sim 1\%$) it is necessary to know the IB spectrum from the source. In the first approximation the shape of IB is described by the expression $y(x) = (1 - x)^2 \cdot x$, where $x = \frac{E_\gamma}{Q}$ is the ratio of the energy of the radiated photon to the energy of the decay; the number of photons in the IB spectrum emitted per $K$-capture, is equal to $N = \frac{\alpha}{12\pi} \cdot \left( \frac{Q}{mc^2} \right)^2$, where $mc^2$ is the electron rest mass [7]. For $^{51}$Cr $Q = 750$ keV and $N = 3.8 \cdot 10^{-4}$.

However, in the region of low energies the IB spectrum can be distorted in accordance with the structural features of the nuclei of different isotopes [8]. This paper describes the measurement of the IB spectrum from $^{51}$Cr performed on germanium semiconductor detector (SD) with unsealed point-like $^{51}$Cr source of low activity.
2. Measurements

Measurements of the IB spectrum from $^{51}$Cr were performed on the setup consisting of SD and lead collimator with a thickness of 10 cm with a cylindrical hole of 1 cm diameter, which axis is directed to the center of the detecting Ge crystal. The collimator restricts the area of the detector crystal, within which the detecting efficiency for photons of a fixed energy are the same.

The $^{51}$Cr source with activity of 1 GBq was located on the axis of the collimator, at a distance of ~1 m from it. The count rate in the detector was ~ 50 s$^{-1}$, and the number of overlaps was negligible.

The spectrum of photon radiation from $^{51}$Cr consists of two parts – a line of 320 keV (10% yield) and IB ($3.8 \times 10^{-4}$). Because of the large difference in the intensities (I(320)/I(IB) ~ 300), the count rate in the detector was determined by the intensity of the 320 keV line; besides that, Compton "tails" in the distribution of pulses from the photon 320 keV in the detector excluded the possibility of the IB measurement in the energies range less than 320 keV. Therefore, the IB spectrum can be measured only for energies of photons above 320 keV.

Energy range for the measurements in the detector is limited to 3 MeV and includes the main part of the photon lines from the natural background radioactive sources and photons from radioactive impurities expected in the $^{51}$Cr source.

In order to accurately determine the activity of the $^{51}$Cr source, that used to measure the spectrum, we also used a second $^{51}$Cr source, having a low activity (10 kBq). The activity of the second source could be accurately measured in the NaI detector in conditions of 4$\pi$-geometry, and a small number of random coincidences of pulses. The wall thickness of the NaI crystal is 10 cm, and the probability of 320 keV photons detection was above 99 %.

Determination of the activity of the $^{51}$Cr source that was used for IB spectrum measurement was made from the comparison of the number of events in the complete absorption peaks of 320 keV line in the IB spectra of both sources in SD.

The error of the source activity measurement consists mainly of three uncertainties: 1) error associated with the statistics in the complete absorption peak in spectrum of the SD for the low activity source; 2) dimensions of the low activity source which lead to the error of geometrical efficiency for photons from this source in conditions when the source was placed near the collimator; 3) the uncertainty of the decay constant of $^{51}$Cr. The latter derives from necessity of long term measurements of the low activity source in the SP and the NaI detectors. The total error of measurement of activity is ±3.3%.

3. The spectra reconstruction

The spectra of pulses in detectors from monochromatic photons are always complex because a part of the photons that fall into the detector crystal coming out the crystal. Therefore, registration always distorts the continuous spectrum of photons. For detectors with good resolution, i.e. the width of the complete absorption peaks is less than the width of the energy bins one can apply the recurrence formula for the recovery of the spectra using a set of response functions: $y_{2k} = \frac{\sum_{j=k+1}^{N} y_{1j} \cdot y_{0j}}{y_{1kk}}$.

[6]. Here $N$ is the number of bins in the spectrum of the pulses, $y_{2k}$ – number of pulses registered in the $k$-th bin (i.e., the input spectrum of pulses); $y_{0k}$ – the value of the signal at the $k$-th bin in energy spectrum of the photons in the source, i.e. the recovered energy spectrum, which excludes the distortions associated with the effect of the detector. Values $y_{1j,k}$ are the response functions, the probability of registration of the pulse from the photon with energy from bin $k$ in the energy bin $j \leq k$.

Response functions obtained from Monte Carlo simulations for photons of all energy bins. The found response functions were adjusted with the spectra of pulses obtained from irradiating of SP by the standard sources of one or more photon lines ($^{137}$Cs, $^{24}$Na, etc.).
4. Results
From these measurements of the $^{51}$Cr source pulse spectrum the SD background spectrum was subtracted and then the difference spectrum was used for the restore procedure. Restored spectrum was approximated by theoretical IB spectrum (see figure 1).

The lower bound of the interval of the approximation of 360 keV was chosen in the region without impact of the pulses from the 320 keV peak. Overlay of pulses from the 320 keV peak created a noticeable bulge in the spectrum region of 640 keV, which restricts the approximation interval from the high energies to the value of 580 keV. Thus, because of the width of the energy bins of 10 keV the approximation was performed for 23 points in the IB spectrum. The activity of the source found in the approximation differed on 6% from value obtained in measuring the relation of the count rates in a line of 320 keV. The reason for this difference is associated with a large statistical error of the number of events in bins of the approximated spectrum. The error arises because of the count rate of SP is limited by intense detection of photons in 320 keV line, and the count rate of IB photons is comparable to the count rate of the SP background.

5. Discussion
Thus, it is impossible to make accurate measurements of the $^{51}$Cr IB spectrum by applied method due to limitations of the counting rate of SP because of photons of 320 keV line. However, the measurements showed that at energies above 320 keV the spectrum shape is in a good agreement with the theoretical IB curve.

The accuracy in the measurements with intense neutrino $^{51}$Cr source in the experiment BEST will be much higher. This is due to the fact that the source is surrounded by tungsten shield, after which the ratio of the intensities of the photons of 320 keV line and IB is reduced from ~300 to ~1.5, i.e. the relative statistics of IB in the resulting spectra will increase by ~200 times. The decrease in the relative intensity of the line of 320 keV will allow also expanding about 2 times the energy interval of the photons for the approximation.

6. Conclusion
In preparation of the BEST experiment it was reviewed a set of procedures of the spectrometric method for determining of the $^{51}$Cr source activity. The $^{51}$Cr IB spectrum was measured in the range of 360-580 keV, the procedure for the reconstruction of the spectrum using the response function was performed, the magnitude and major sources of errors were determined.
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7. References

[1] Abdurashitov J N et al. 1999 Phys. Rev. C 59 2246
[2] Abdurashitov J N et al. 2006 Phys. Rev. C 73 045805
[3] Hampel W et al. 1998 Phys. Lett. B 420 114
[4] Anselmann P et al. 1995 Phys. Lett. B 342 440
[5] Gavrin V N et al. 2010 arXiv:1006.2103v2
[6] Gorbachev V V and Malyshkin Yu M Instr. and Exp. Tech. 58 418
[7] Anderson E, Wheeler G W and Watson W W 1953 Phys. Rev. 90 606
[8] Martin P C and Glauber R J 1958 Phys. Rev. 109 1307